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THE TECHNICAL REPORT

on the item 0004 of the contract SPC-97-4042
«Experimental Study on Supersonic and Hypersonic Flows
Around Models with On-Board Plasma Generators»
(experimental investigations at Mach number M=4)

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ABSTRACT

In this report, the results of experiments on the contract SPC-97-4042 in the wind tunnel T-113 of TsAGI at Mach number M = 4 and static pressure equal 29 torr are presented. The tests were carried out with three types of axisymmetical models. Two of them were equipped by plasma generators and had the different form of the nose part. In front of the bluntness, these models had the needle. Besides, the nose parts of them were produced of two different isolator materials. The plasma generators were supplied by energy either from the alternating current source of electric power or from the capacity storage. The third type of the model was the body contour of which was close to the optimal one for M = 4 and did not have any generator. The models equipped by plasma generators were produced by MTC, the model of the third type was made by TsAGI.

In all runs, the balance measurements and schlieren photo registrations were carried out. In the experiments with the models equipped by plasma generators, the spectroscopic diagnostic of the discharges by MSU (to the end of determination of rotation and vibration temperatures) and ordinary photography were also fulfilled. Full results of the aerodynamic experiments and significant results of other investigations will be further presented. In these experiments, the effect of the drag decrease at the discharge presence did not exceed 14 % and the model of the optimal form had the drag coefficient less than the models with working plasma generators.

INTRODUCTION

In the physical investigations carried out in some Russian Research Institutes, the effect of an anomalous propagation of the shocks through the plasma of globe discharges was studied (see, for example, [1 - 3]). In particular, the effects of the shock intensity decrease were observed. Then the shock wave dispersion existence were confirmed by the work [4] in USA. On the base of the studies of [1 - 3], the assumption was made by some investigators that the electric discharges application can become the effective method of the aerodynamic characteristics improvement. In this case, reproduction of the drag reduction effect would seem to take place at the same discharges ignitions on the models in supersonic flows. Some experiments which were carried out in supersonic wind tunnels with models equipped by plasma generators showed that the effect of the aerodynamic drag decrease indeed can be considerable (see, for example, [5,6]). However a doubt of the specialists of TsAGI was that those investigations were fulfilled with the models which had an imperfect aerodynamic form and the drag decrease effects were demonstrated at the large energetic expenditures non-adequate to those in experiments of the works [1 - 3].

At TsAGI, the experimental base was created for objective estimations of possibilities of plasma methods of the aerodynamic characteristics improvement which were suggested by the workers out of these methods and for the help in effectuation of the corresponding experiments in the classical wind tunnels with well known and stable parameters of the flows. Together with the axisymmetric model of MRTI which had a semispherical bluntness and a needle in front of it (it was supposed that this model would be used for the first experiments and for securing of succession of the results), two type of the models were designed for the experiments in the supersonic flow. One of them had a conic bluntness and the same type of the plasma generator as the model of MRTI. The model of the second type did not have any plasma generator but the form of its nose part was close to the optimal aerodynamic one. We supposed that effect of the electric discharge influence on the aerodynamic drag would reduce at passage to the model with conic bluntness which had a more perfect aerodynamic form than the model of MRTI. It was interest also to compare the drag coefficients for the models with the working plasma generators and for the model having the optimal aerodynamic form without a plasma generator.

In the previous investigation, results of which were delivered at the workshop in Colorado Springs, the experiments were carried out only with the model of MRTI. In those experiments [7], it was found that the effect of the drag decrease could be considerable if the electric energy input in the discharge was large enough but it reduced at the drop of this input and was equal zero at the necessary small energetic expenditures. These results did not contradict the

hypothesis of the heat influence of the discharges on the aerodynamic characteristics.

In the frame of the contract SPC-97-4042, for the model equipped by Dr. Klimov' plasma generator with semispherical nose part, we supposed to receive the results analogous those which were presented in Colorado Springs and to compliment them by the results of the spectroscopic measurements of the rotation (gas) and vibration temperatures in the discharge received by MSU. However in the process of the production of the models of this type by MTC, some constructive changes were made (see below) seemed insignificant on the face of it. Besides, the type of the electric supply of the plasma generator was changed. As a result, the values of the effect of the drag reduction turned out to be significally different from those in previous experiments. These new values of the effect were compared with those for the model with the on-board plasma generator which had the conic bluntness and the needle in front of it. For the last type of the model, the spectroscopic measurements of the gas and vibration temperatures in the discharge were also made by MSU. The experimental values of the drag coefficient for these models were compared with that for the model which had the form close to the optimal one. The basic measurements were complimented by Tepler and ordinary photo registrations.

The detailed elucidation of the questions concerning the plasma generators and spectroscopic measurements which were applied in this work was placed in the reports [8,9].

CONDITIONS OF THE EXPERIMENTS

Experiments were carried out in the wind tunnel T-113 of TsAGI at Mach number M = 4. The detailed description of T-113 and its possibilities were given in [10]. Here the basic parameters of T-113 are presented.

The wind tunnel T-113 is the supersonic set up of periodical action, non-return flow and closed-jet type. The different values of Mach number are realized with help of series of nozzles. The working part has the square cross section of 600 by 600 mm and the length of 1.9 m. In the setting chamber, there are a honecomb and five deturbulization grids that provides the level of pulsations in the supersonic flow less than 1%. For realization of a low static pressure in the working part of the wind tunnel (in particular, 29 torr at Mach number M = 4), supersonic ejectors are used.

For measurements of summary aerodynamic characteristics, the wind tunnel has the four-component electro-mechanical balance. In fulfilled experiments only drag and lift were measured. The errors of measurements are characterized by the following mean-square values: for D - .6 N, for L - .5 N. The transitive time of the balance and its filters is about 1 sec.

The pressure measurements are carried out by the standard pressure transducers. In particular, the base pressure was measured in two points: at the bottom of the model and at the model sting bottom. The errors of the pressure measurements were: 400 Pa for the total pressure, 40 Pa for the static one and 100 Pa for the base pressure.

The registration of outlet signals from the balance transducers and pressure ones during every run was carried out by the analog-to-digital sixteen bit converter which was controlled by the wind tunnel computer. The time cycle of the interrogation of all channels took about .3 sec.

The optical investigations of a flow over the models were carried out by the Tepler apparatus (of Zeiss firm) with the optical field diameter of 260 mm and the flash duration of about 4 mcs. This allowed to receive almost an instantaneous picture of a flow over the model. However the shutter of the camera was closed manually. Therefore the blurred image of the discharge superimposed itself on the basic image of a flow over the model.

For the spectroscopic measurements of the rotation temperature and the vibration one, MSU equipped the wind tunnel by the spectrograph STE-1. As it was mentioned above, Tepler and spectrograph photoregistations were carried out in every run and often in each regime in the run.

At effectuation of experiments with plasma generators mounted on the models, the additional system was acted which provided the record of the current/voltage values of the generators and synchronization of these records with the balance reading. It consisted of a multi-channel bifilar oscillograph, an electron oscillograph with a memory tube and a block of operation. The reference of the balance reading to the time of the generator work was carried out on the bifilar oscillograph by the record of the signal marks from the wind tunnel computer corresponding to the moments of the balance channel interrogation.

The wind tunnel T-113 has the capacity storage of 4,800 mcF and voltage up to 5 kV for plasma generators supply. Therefore some runs were carried out with this source of the electric energy. However the basic attention Dr. Klimov spared to the experiments in which the generators received the energy from the alternating current source of 50 Hz - frequency. In fulfilled experiments, the change of the initial level of the discharge currents was set by variation of resistors in the discharge circuits.

Before the experiment, the readiness of all systems of the wind tunnel was examined by the standard procedure of this set-up and preparation or verification of the electric supply circuits, the electric parameters registration circuits, the Tepler system, the MSU optical system were carried out.

The following succession of operations were being fulfilled during every run of the wind tunnel at the angle of attack equal zero. The channels of the total, static, base (two points) pressures and D-, L- channels were interrogated by computer. Further the time diagram of the run was following:

Operations	Time, sec
Start of the run	0
Opening of gates and starting of the wind tunnel to the necessary regime; exposure for damping of balance	0 - 5
The exposure for the total stabilization of the wind tunnel regime	5 - 7
Interrogation of all pressure channels, balance channels and channel of the angle of attack by computer	7 - 8
The oscillograph switching on for the current/voltage registration	8 - 9
Transition of the computer to the continuous regime of interrogation; possible photo registrations of a flow over the model without plasma	9 - 10
Start of the plasma generator work	10
Interval of the work with the plasma generator; possible photo-registrations and optical measurements by MSU	10 - 30
Finish of the work with the plasma generator	30
The registrations of parameters after the plasma generator disconnection	30 - 33
Cessation of the continuous interrogation of drag, lift, and base pressure channels	33
The oscillographs were switched off, but there was interrogation of the channels of total, static, base pressure and drag, lift channels	33 - 36
Closing of the wind tunnel gates	36 - 39
Interrogation of the channels of total, static, base pressures and drag, lift, channels	39 - 42
The end of the wind tunnel work	42

Note: The duration of the work with the plasma generator of 20 sec is taken tentatively and includes the pauses for the change of its regimes. In fact, this duration was from 18 to 25 sec.

The data processing of every run was carried out by the standard methods of the wind tunnel T-113. Some corrections were introduced, at that, in the results. They were bound, in particular, with the aerodynamic loads that act on the balance elements and on the elements of support of the model because of weak streams in the plenum chamber. Besides, the corrections were introduced on small flow angularity, on the tail sting deformation under the aerodynamic load influence and also on the base pressure. The correction on the last was introduced from the condition of putting of the pressure at the bottom cut of the model to the static pressure of the flow.

MODELS DESCRIPTION

The general view of the contours of the models are presented in Fig.1 -3. Two types of the models named A and B (Fig. 1, Fig. 2) were equipped by the MRTI/MTC plasma generators. Originally the isolator of these models was produced of caprolon (synonyms: polyamid 6.6, acrylic plastic, caprolactam). However the preliminary experiments (see, for example, [9]), and experiments of this series, showed that caprolon was subjected to the considerable erosion under the electric discharge influence. Therefore, besides of the models A1 and B1 with the nose part of caprolon, MRTI/MTC worked out the plasma generators in which the radiotechnical ceramic was used for the basic isolators (models A2 and B2). The models with these isolators had a certain difference in the dimensions from the models with caprolon ones.

The model of type A (Fig 1) was consisted of the dielectric conic nose part with a semispherical bluntness and a cylindrical body of 40 mm - diameter of steel or caprolon. According to specified data, the radius of the bluntness was 13.5 mm for the conic body of caprolon and 10.5 mm for the body of ceramic. The half-angle of the cone was about 6^0 if the nose part of the model was produced of caprolon and about 5^0 for the analogous body of ceramic. The cone had eight small electrodes of one sign accommodated flush to its lateral surface. These electrodes were arranged at the origin of the cone part behind the semispherical bluntness. The other electrode was the sharp (about 9.5^0 - full angle) copper cone at the head of the needle. The shell of the cylindrical part of the needle was a ceramic tube of 5 mm - diameter. From Fig. 1, it is seen that the models A1 and A2 had also other differences of dimensions besides the above ones. These differences were conditioned by the technology of the production of the model of radiotechnical ceramic.

The contour of the model of type B (Fig 2) was suggested by TsAGI as having more aerodynamic form than model A. As the model A, it consisted of the dielectric conic nose part and the cylindrical body of 40 mm - diameter but the nose part had the conic bluntness which the needle was mated to. The half-angle of this bluntness equaled 17.5^0 if the blunted body was produced of caprolon and about 20^0 for the analogous body of ceramic. The half-angle of the basic cone part was about 6^0 for the nose part of caprolon and about 5^0 for that of ceramic. (These data were also specified in comparison with to the data which had been given in the intermediary report). The plasma generators for these models were analogous to the generators for the model of type A. Eight electrodes of the generator were arranged at the origin of the basic conic part. One can see from Fig.2 that the models B1 and B2 had the different form in great measure. This difference also was conditioned by the technological difficulties of producing of required form isolators of radiotechnical ceramic.

The third model C was also suggested by TsAGI. It had the profile close to the optimal one at the maximum diameter of 40 mm and did not have the needle and electrodes (Fig. 3).

In Fig. 4-9, the inner view of the models and the details of them are shown. In Fig. 4, the cut of the model A1 with the semispherical bluntness of the nose part of caprolon and with the cylindrical part of steel is presented. Majority details of the model B1 was those as for the model A1. In Fig. 5-6, the sketches of details of these models are given. The model B1 is received from the model A1 by change the nose part of the semispherical form on that of the conic form (Fig. 5). In Fig. 7, it is shown how the metal body of the models A1 and B1 is changed on the plastic one. In Fig. 8, the assembly sketch of the model A2 with the ceramic nose part and the plastic body of the cylindrical part is presented. The analogous sketch for the model B2 is shown in Fig.9. The details of the models A2 and B2 were assembled by the cast of the plastic gum inside the body of each model with further solidification of it (Fig. 8,9).

ABOUT THE TEST PROGRAM

The program of experiments has been worked out in according to the technical task. For the model of type A, six runs were foreseen to be carried out. The electric parameters and the power level of the plasma generators in the tests and the goals of the runs were assumed to be set by Dr. A. Klimov. In each run , the values of C_D and C_L of the model were supposed to measure by the balance as a function of time. Also the records of the discharge current and the voltage across the discharge gap synchronized with the balance reading as well as ordinary photographs of the discharge were to be received. Originally there was intention to carry out the spectroscopic investigations of the discharges in four runs and Tepler

photography in two runs, but afterwards the apparatuses were arranged so that the spectroscopic and Tepler photos could be received in every run. Besides, going towards Dr. Klimov's wishes, the duration of the run was increased to have possibility of registration of three or two various regimes of plasma generators.

For the model of type B with the conic blunted head and the needle, there was the intention to make seven runs. In each run, the same aerodynamic characteristics as for the model of type A were to be measured and the analogous integral parameters of the discharges were to be recorded. The primary intention to make the spectroscopic and Tepler investigations in different runs were substituted by those in every runs.

For the model C with the profile close to optimal one without needle and electrodes, it was suggested to carry out two runs in various days . In each run, the values of C_D were to be registrated by the balance and Tepler photographs of a flow over the model were to be taken.

The test program had been composed before the preliminary experiments [9] and, consequently, we did not know that, in course of the investigations, we would be compelled to fulfill experiments with the models A and B having two type of isolator for the nose parts. Therefore the schedule of the runs contained the general description of the experiments without division according to the type of the nose part.

BRIEF REVIEW OF THE RUNS

In many cases, the experiment with the model equipped by a plasma generator led to necessity of restoration of the working state of the plasma generator or the model. In these cases, the model of other type could be installed in the working part of the wind tunnel. To escape a mess in the numbering of runs, we present at first the runs, perhaps for various models, in that succession in which they were made in the course of the investigation and accompany this description by the brief characteristics for each run. At that we conserve the wind tunnel numbering of runs. Then we shall give the description of the results received in each run with presentation of the results of the balance records processing.

Run No 1302. This was the run for the model C which had the contour close to the optimal one and did not have a plasma generator. The experiment showed that the value of C_D for this model equaled about .095.

Run No 1303. This was the first run for the model A1 with caprolon isolator for the nose part and the semispherical bluntness of it. The plasma generator received the energy from the alternating current (AC) source. The principal scheme of this source connection with the plasma generator and measurements is shown in Fig. 10. The electric scheme of the plasma generator was assembled so that the conic electrode of the needle was kept under the potential of the wind tunnel i.e.

under the potential of «ground». Before the discharge ignition, the model had the drag coefficient equal .225. The plasma generator was twice switched on at various regimes of the supply: 1) $I_d \approx 2.4$ A, $U_d \approx 1{,}500$ V, 2) $I_d \approx 1.44$ A, $U_d \approx 1{,}800$ V, where I_d and U_d are the amplitude values of the discharge current and the voltage across the discharge gap. The principle of determination of these values is given in Fig. 12. The visual observation showed that discharge burnt only on the lateral surface of the model between the electrodes arranged on this surface and was drifted down the model. The electrode of the needle did not participate in the creation of this discharge. The effect of the drag decrease was low.

Note: The plasma generator having some electrodes of one sign is a complex system in which different currents could flow to various electrodes. Therefore the voltages across the discharge gap for these electrodes could have a different value. In particularly, this value could be very high if the current to the concrete electrode equaled zero. It could be low if the electric breakdown took place to this electrode inside the model. In experiments which were carried out, the voltage was measured only for one of electrodes. Therefore the presenting values of U_d has only a contingent value. This note concerns also the values of power which will be adduced below.

Run No 1304. In this run with the model A1, the attempt was undertaken to elucidate the reason why the discharge burnt only on the lateral surface of the model. The electric scheme of the plasma generator connection to the power supply unit was such as in the previous run. Before the discharge switching on, the initial value of C_D turned out to be .234. The plasma generator was switched on three times at the following regimes of the AC discharge which had the less values of the current than in the previous run: 1) $I_d \approx 1.6$ A, $U_d \approx 750$ V, 2) $I_d \approx .8$ A, $U_d \approx 750$ V, 3) $I_d \approx .6$ A, $U_d \approx 750$ V. In this case, the discharge also burnt as a ring along the lateral electrodes in spite of the reduction of the maximal value of the current. As in the previous run, the effect of the drag decrease was low.

Run No 1305. The experiment with the model A1 was continued without overhaul of it but the electric scheme was changed for the plasma generator supply from the capacity storage i.e. by the quasi-steady current. The principal scheme of the electric supply and measurements in this case is shown in Fig. 11. The lateral electrodes had the anode potential. The initial value of the drag coefficient before the discharge ignition was .217. Again the discharge burnt on the lateral surface of the model at the voltage of 240 V. The record of the current was absent. The effect of the drag reduction was about 2 %.

After this run, the model was demounted and, inside of it, marks of the electric breakdown between one of the lateral electrodes and the «ground» were disclosed. This examination explained the cause of the abnormal discharge burning and the current record absence on the bifilar oscillograph since the current flowed on the «ground» evading the shunt.

Note: The runs No 1306, 1308, 1310, 1312, 1319, 1320 were both technological ones or the discharges did not ignite at feeding of the voltage to the electrodes of the plasma generator or there was an evident breakdown inside the model. In the last two cases, the runs of the wind tunnel were ceased.

Run No 1307. The experiments with the model A2 that had the semispherical nose part of radiotechnical ceramic were being begun. The scheme of the connection of the electrodes of the plasma generator and the source of AC current was those as in the runs of No 1303 and 1304. The aim of the experiment was to obtain the drag reduction effect at the decrease of the discharge current. The initial value of C_D equaled .22. The plasma generator was switched on three times and the following regimes of the discharge were realized: 1) $I_d \approx .3$ A, $U_d \approx 2{,}400$ V, 2) $I_d \approx .5$ A, $U_d \approx 2{,}100$ V, 3) $I_d \approx 1$ A, $U_d \approx 1{,}800$ V. The discharge burnt only on the lateral surface of the model and, in the range of the errors of measurements, the influence of the discharge on the drag was practically absent.

Run No 1309. That was the first run with the model B1 which had the conic bluntness of the nose part of caprolon (Fig. 2). The scheme of the connection of the plasma generator to the source of the AC current was that as for the model A1 in runs No 1303, 1304. The initial value of C_D before the discharge ignition was .156 and, as one can see, it was noticeably less than that for the models A1 and A2. The discharge was ignited three times, the following regimes being realized: 1) $I_d \approx .95$ A, $U_d \approx 1{,}350$ V, 2) $I_d \approx 1.4$ A, $U_d \approx 1{,}500$ V, 3) $I_d \approx 2.4$ A, $U_d \approx 1{,}350$ V. The visual observation showed that, at first, the discharge burnt from the central electrode of the needle to the lateral ones. Then the electric breakdown happened to the metal cylindrical part of the model, though it was insulated from the «ground», and, from this part, went to the grounded stud of attachment of the model to the sting of the balance. After that, the discharge burnt downstream from the lateral electrodes. The influence of such discharge on the drag was very small.

Run No 1311 was the second run with the model that had the form close to the optimal one. It was carried out in the middle of the program instead the end of it since the pause arose in the tests with the models A and B. The value of C_D was again .095 as in the run No 1302.

Run No 1313. This was the second run with the model B1 at the discharge feeding by AC current. Beginning with this run, the cylindrical part of all the models was made of caprolon. The scheme of the plasma generator connection to the AC current source was that as in the previous runs. The value of C_D before the discharge ignition was about .15. The discharge was switched on three times and the following regimes were realized: 1) $I_d \approx 2.25$ A, $U_d \approx 2{,}800$ V, 2) $I_d \approx 1.75$ A, $U_d \approx 2{,}650$ V, 3) $I_d \approx .88$ A, $U_d \approx 3{,}000$ V. The discharge burnt as a cord from the central electrode of the needle to the plate of the lateral electrodes then as a «ring» around them and was very drifted downstream. The effect of the drag decrease was registrated on the level of 3 %.

Run No1314. This was the new run with the model B1 at the plasma generator feeding by AC current. The goal of the run was to study of the effects at the larger currents than in the previous experiment. The initial value of the drag coefficient before the discharge ignition was .155. Three regimes of the discharge were realized: 1) $I_d \approx 3.4$ A, $U_d \approx 2{,}700$ V, 2) $I_d \approx 1.42$ A, $U_d \approx 2{,}700$ V, 3) $I_d \approx 1.05$ A, $U_d \approx 3{,}300$ V. The discharge burnt between the central electrode of the needle and lateral those both as two cords or the alternated one. They unfolded as a ring along the lateral electrodes and then the discharge was drifted downstream. At the second and third regimes, the electric breakdowns were observed in the plenum chamber of the wind tunnel in which the mechanism of the balance was arranged. The maximal value of the drag decrease effect was about 6 %.

Run No 1315. The experiment was carried out with the model A2 (ceramic nose part with semispherical bluntness) at connection of the plasma generator to the capacity storage. The copper conic electrode of the needle was cathode. Through the shunt, it was connected to the ground. The initial value of C_D before the discharge ignition equaled about .2. The initial values of the discharge current and the voltage across the gap were 2.5 A and 1,500 V, accordingly. The duration of the discharge was about 6.7 sec. The discharge burnt between the central conic electrode of the needle and the lateral electrodes. The drift of the discharge downstream was also observed. Probably, in the end of the generator work, an electric breakdown took place inside the model. At the discharge, the value of C_D decreased to .17. But after the discharge cessation, the coefficient C_D restored itself only to value about .184. It was interest to elucidate weather this result was not the effect of «afteraction of the plasma». To this end, the run No 1316 was carried out in about 15 minutes after the run No 1315.

Run No 1316. This was the run with the model A2 plasma generator of which was recommutated so that the central electrode of the needle was anode and the lateral those were cathodes. The plasma generator was fed from the capacity storage. Before the discharge ignition, the value of C_D was about .17, i.e. was close to its value in the end of the run No 1315. Consequently, the effect of the non-restoration of C_D in the end of the run No 1315 was bound, probably, with a change of the model form but was not the effect of plasma afteraction. The initial values of the current and the voltage between electrodes were 2.9 A and 1,500 V, accordingly. The duration of the discharge was about 10.6 sec. The discharge burnt from the needle as some cords. The electric breakdown was also observed inside the model. The maximal value of the drag decrease effect was less than 6 %.

Run No 1317. The experiment was carried out with the new model of type A2. The discharge was fed by AC current, the potential of the electrode of the needle being close to the «ground». The goal of the run was to determine the value of the effect at low discharge currents. The initial value of C_D was about .22. The plasma generator was switched on two times. In both cases, the amplitude of the current was about 1.13 A and the voltage across the discharge gap equaled

approximately 600 V. At the discharge burning, the drag decrease effect was about 7 %. After the discharge cessation, the coefficient of C_D became equal about .22.

Run No 1318. In this run, the experiments with the model A2 were continued, the plasma generator being fed from the AC power source. The potential of the electrode of the needle was close to that of the «ground». The initial value of C_D was about .2. The discharge was ignited two times at the following values of the current and voltage between the electrodes: 1) $I_d \approx 2.8$ A, $U_d \approx 300$ V, 2) $I_d \approx 3.1$ A, $U_d \approx 300$ V. The drag decrease effect was on the level of 11 % but after the final discharge switching off the value of C_D restored itself only to the value of about .19.

Run No 1321. This was experiment with the model B2. The discharge was fed by the alternating current at the scheme analogous that in the runs No 1303, 1304. Before the discharge ignition, the drag coefficient of the model was .13. Two regimes of the discharge were realized: 1) $I_d \approx .75$ A, $U_d \approx 900$ V, 2) $I_d \approx 2.6$ A, $U_d \approx 450$ V. The maximal effect of the drag decrease took place at the second regime and equaled about 6 %.

Run No 1322. In this run, the aerodynamic characteristics of the model B2 was investigated at the plasma generator supply by more intensive alternating current ($I_d \approx 3.9$ A, $U_d \approx 450$ V). The initial value of C_D was about .13. The electric scheme of the plasma generator was that as in previous runs. It was noticed that the discharge burnt as a cord from the nose electrode to the lateral ones where it became as a ring. The discharge had strong drift downstream. The maximum value of the drag reduction effect was about 8 %.

Note: runs No 1306 and 1310 were fulfilled with the model B1. But in the former, the AC discharge ignited inside the model, and in the last, the DC discharge quite did not ignite.

RESULTS OF EXPERIMENTS

In this division, we grouped the runs according to the type of the models. At first we shall discuss the results of the experiments for the models equipped by the plasma generators.

Since further the values of the power supplied to the discharges will be indicated we give the scheme of estimation of the effective power for the AC discharges for concrete experiments.

In Fig 12, left, the character of change of the discharge current and voltage across the discharge gap at this case are schematically shown for one period. In those figure, to the right, the records of the current and voltage on the screen of oscillograph are conventionally given. Zeros of the current and voltage are not combined. In Fig. 13, this schematic drawing is illustrated by the real records of the current and voltage in runs 1303 and 1309 (*a* and *b*, correspondingly).

The power supplied to the AC discharge are

$$N = (1/T)\int_0^T I \cdot U \cdot dt,$$

where T is the process period.
For estimations of N, the following simplified conventions were used.
It was supposed that the voltage across the discharge was constant in the confines of the half-period of current (see photo in Fig. 13). It was also supposed that this current changed as sin ($\omega_1 t$) out of those intervals of time when it was zero.
Then, in the formula for N, the integral calculated on two half-periods of the current would equal $2TI_dU_d/\pi$. Presence of the current pauses leads to decrease of this value. The energy loss decrease for the period because of the pauses presence is proportional difference of products of the mean value of the current by periods for the genuine sin ($\omega_0 t$) corresponding to the frequency of 50 Hz and for the real curve which had a less period. On the base of analysis of the current curves, we supposed that the period of the real curve was about .8 from the period of genuine sin ($\omega_0 t$). Therefore the effective value of N was calculated as

$$N \approx .8 \cdot (2/\pi) U_d I_d.$$

Models type of A
(S - models in MTC designation)

For this group of the models the initial value of coefficient C_D without discharge equaled about .2 - .22, i.e. it was larger than C_D for the modes types of B and C.

In Fig. 14, the results of measurements of coefficients C_D and C_L are presented as a function of time for the model A1 in run 1303. The abbreviation ACD means the interval of time during of which the AC discharge was switched on. In the lower plot, the dependence of the coefficient C_{DB} of the base drag on time are presented. At the first switching on of the plasma generator, the effective value of power input was about 1.84 kW. At the second ignition , it was about 1.3 kW. In both cases, the effect of the drag decrease was small and its maximal value equaled 2.2 %. It is seen that, after the first discharge switching off, the record of the balance reading went out on the steady state during about 1.2 - 1.5 sec. This time agrees with the transitional time of the balance and its filters. The value of C_L was also small both in this and in following runs. The difference of C_L from zero, probably, was bound with some non-symmetry of the model. The coefficient of

C_{DB} did not change at the discharge ignition i.e. the discharge did not influence on the base pressure.

In Fig.15, Tepler and ordinary photographs received in this run are presented. In Fig 15,*a*, the structure of the shock system from the needle and from the semispherical bluntness as well as the structure of the separation zone are distinctly visible. From Fig. 15,*b*, where the photo of a flow over the model is presented at the first discharge igniton, it is seen that the electrode of the needle did not participate in the creation of the discharge and the discharge was drifted downstream. The cause of it was disclosed later, when, after run 1305, it was elucidated that the electric breakdown took place between the wires with help of which potentials were led to the central electrode of the needle and to one of the lateral electrodes. It is also seen that, out a zone of the discharge burning, the structure of the shocks was not changed noticeably because of the discharge presence.

In Fig 16 and 17, the basic results received in the run No 1304 for the model A1 are shown. The plasma generator was switched on three times and the effective values of AC power supplied to the discharges were about .6kW, .3kW, .23 kW. From Fig.16, where data of the balance reading are presented, we found that maximal values of the drag decrease effect were 2.5, 1.7 and 1.3 %, accordingly. The results of Tepler and ordinary photography in this run are presented in Fig. 17. In particular, Fig. 17,*b*, gives information about a flow over the body and the character of the discharge at the second ignition of the plasma generator. Here there were the same peculiarity of the discharge burning as in the previous run. Since the discharge burnt only on the lateral surface of the model, efficiency of it was small.

The experiment with the model A1 was continued in run 1305 without overhaul of this model but the electric scheme was changed for the plasma generator feeding from the capacity storage, the lateral electrodes having the anode potential. The records of the coefficients of C_D, C_L, C_{DB} during this run are presented in Fig 18. The abbreviation DCD is designation of the interval of time during which the discharge burnt. One can see that the initial value of C_D before the discharge was .217 and the maximal value of the drag reduction effect was only 2.2 %. As it was pointed out above, the cause of very low value of the effect in this case was concluded in a short circuit of the cathode wire and one of anode wire inside the model. The photograph of a flow over the model and the ordinary photograph of the discharge for this case are given in Fig. 19,*a*,*b*. It is distinctly seen that the discharge burnt only on the lateral surface of the model.

Experiments with the model A2 that had the nose part with semispherical bluntness of radiotechnical ceramic were begun by run 1307 at supply of the plasma generator by AC current. The goal of experiments was to obtain the data of the drag reduction effect at low values of the current. Three regimes were realized consecutively with the following amplitude values of the current: .3 A, .5 A, 1 A.

The records of the coefficients C_D, C_L, C_{DB} are presented in Fig. 20. In the plot for C_D, one can see only hints of the discharges influence on the aerodynamic drag. In Fig. 21 and Fig. 22, Tepler photographs of a flow over the model and ordinary those of the discharge burning are shown. Photo in Fig 21,*a* illustrates a flow over the model without discharge. The photos in Fig 21,*b*,*c*,*d* and Fig 22, *a*, *b*, *c* shows the images of the discharge burning at the amplitude values of AC current .3 A, .5 A and 1 A, accordingly. One can see that in all these cases, the discharge burnt only on the lateral surface of the model and, probably, did not exert influence on the system of the shocks.

Two runs, No 1315 and 1316, were carried out for the model A2 at supply of the plasma generator by a current from the capacity storage. The model A2 was modified so that the cylindrical part of it was made of caprolon. In run 1315, the central electrode of the needle was cathode. In Fig 23, the copies of records of the discharge current and voltage between the electrodes of the plasma generator are shown. During the discharge, its current changed from 2.5 A to .85 A and the voltage from 1,500 V to about 2,500 V. The records of coefficients of C_D, C_L, C_{DB} are presented in Fig. 24. In this case, one can see the noticeable effect of the drag decrease. The maximal value of the effect (13.3 %) took place at the second sec. after the discharge ignition. At this moment, the electric power supplied to the discharge was about 2.5 kW. The effect that C_D did not restored to the initial value after the discharge cessation we discussed above. One can see that the discharge presence did not exert influence on the base pressure. The character of the discharge burning in this run, one can see in Fig 25 where Tepler and ordinary photographs are presented for this case. It is distinctly seen that, in this case, the discharge burnt between the central electrode of the needle and the lateral ones i.e. occupied the separation zone.

As it was noted above, run 1316 was made in about 15 minute after run 1315 to the end to convince that a low value of coefficient C_D after run 1315 did not bind with «afteraction of plasma». Together with this goal, it was interest to elucidate what effect of the drag reduction gave the plasma generator at the inverse polarity of its electrodes. In Fig. 26, copies of records of the discharge current and the voltage through the electrodes as a function of time at the generator feeding from the capacity storage are shown. The records of balance readings in this run are presented in Fig. 27. From the plot for the coefficient C_D, we found that maximal value of drag decrease effect equaled 5.7 % At this moment, the power supplied to the plasma generator was about 2.6 kW ($I \approx 1.5$ A, $U \approx 1.75$ kV). However, it is not clear what part of this power got out with the breakdown inside the model. One can also see that the value of C_D increased to the end of the discharge and became bigger than the initial value. This was bound, probably, with a change of the model geometry under discharge influence. In Fig. 28, the photographs of a flow over the model without the discharge (*a*), at burning of it (*b*), and an ordinary photograph of the discharge burning (*c*) are given. One can

see that, in this case, the discharge burnt between the central electrode of the needle (anode) and the lateral electrodes (cathodes). As it was noted above, this burning represented a system of some non-steady cords.

Runs 1317 and 1318 were carried out again for model A2 at the plasma generator supply by alternating current. The goal of the run 1317 was to determine the value of the drag reduction effect at the low power expenditures. In this run, the effective power was about .35 kW. The plasma generator was switched on two times. The results of balance records are presented in Fig. 29. At the first switching on of the discharge, the value of C_D decreased from .223 to .211 and the effect of the drag decrease was 5.4 %. After the discharge switching off, the drag coefficient increased to .221 i.e., practically, to the initial value. At the second discharge ignition, the coefficient of C_D reduced to value .206, i.e. the effect of interest was 6.8 %. The concluded value of C_D, after the generator switching off, was .22. For this run, we can present only ordinary photographs (Fig. 30) of the discharge for the both switching on of the plasma generator (*a* and *b*, correspondingly).

In run 1318, the amplitude of the discharge current was increased. At the first switching on, it was 2.8 A ($U_d \approx 300$ V), at the second regime it was about 3.1 A ($U_d \approx 300$ V). At the first regime, the drag coefficient decreased from .205 to .182 (Fig. 31) and the maximum value of the drag decrease effect was 11.2 % at the effective power equal .43 kW. After the discharge switching off, the value of C_D restored to $C_D = .194$. At the second regime, the coefficient C_D decreased to the value .172 and the effect of drag decrease was 11.3 % at the effective power about .47 kW. After the second discharge switching off, the value of C_D restored to .186. This showed that geometry of the model changed under the discharge influence. In Fig 32, Tepler and ordinary photographs are presented for both regimes (*a* and *c* - for the first, *b* and *d* - for the second). It is seen that in this run the AC discharge burnt between the central electrode of the needle and the lateral electrodes.

Models type of B
(C-models in MTC designation)

As it was noted above, for the models type of B, only AC discharges were realized. In runs 1309, 1313, 1314, experiments were carried out for the model B1 which had the conic bluntness of caprolon. For this model, the initial value of C_D was about .15 - .16 i.e. it was noticeable less than for the model type of A.

Records of coefficients C_D, C_L, C_{DB} for the run 1309 are presented in Fig. 33. The values of the effective power supplied to the plasma generator at three regimes switching on of it were about .65, 1.1, 1.65 kW. The discharge influenced very weakly on the drag. Corresponding values of the drag decrease effect were 1.2 %, 1.2 % and 2.5 %. In Fig. 34, the photographs of a flow over the model and the discharge burning are presented. Comparison of the received structure of a

flow around this model without discharge (Fig.34,*a*) and analogous structure for the model with the semispherical bluntness (see, for example, Fig. 15, *a*) shows that in the former the separation zone practically was absent and the bow shock went from the angle between the needle and the surface of the conic bluntness. Probably, such structure of the flow deteriorated conditions of ignition and burning of the discharge. As it was pointed out above, in a certain moment, the discharge threw itself to the ground stud of the model attachment. In Fig.34,*b*, the ordinary photograph of the discharge before this moment is presented. In Fig. 34,*c*, the Tepler photograph of a flow over the model and the discharge after this moment are given.

Beginning with run 1313 the cylindrical part of the model was made of caprolon and the stud was insulated by a gum. This allowed more sure to create the discharge between the central electrode of the needle and lateral electrodes. In Fig. 35, temporal dependencies of coefficients C_D, C_L, C_{DB} are shown. The values of effective power supplied to AC discharge were about 3.2 kW, 2.4 kW and 1.35 kW. At these values of power, the maximum values of the drag decrease effect were 3.3 %, 2 % and 2.6 %, accordingly. In Fig. 36, Tepler and ordinary photographs of a flow over the model and discharges are presented for the first (Fig.36,*a*,*c*) and the third (Fig.36,*b*,*d*) switching on of the discharge. It is distinctly seen that the discharge burnt as a cord from the central electrode of the needle to the lateral electrodes where it accepted a form of ring and then was very drifted downstream.

In run 1314, the calculated values of the power supplied to the AC discharge consecutively were about: 4.7 kW, 2kW and 1.8 kW. The records of the balance reading are shown in Fig. 37. The maximal values of the drag decrease effect in this three cases were: 5.8 %, 2.6 % and 3.2 %. In Fig. 38, Tepler photographs of a flow over the model are given for the case when the discharge was absent and for three levels of the power indicated above. One can see relaxation of the intensity of the discharge and non-steadiness of the geometry of it. In Fig. 39, the ordinary photographs are given at the first and at the second ignition of the discharge. In these photographs, the filament structure of the discharge and strong drift of it downstream are distinctly seen..

Runs 1321 and 1322 were carried out with the model B2 nose part of which had the conic bluntness of the radiotechnical ceramic. The initial value of the coefficient C_D was .13 in both cases, i.e. less than for the model B1. In run 1321, the plasma generator was switching on twice at the following consecutive regimes: about .34 kW and about .6 kW of the power input. The records of the coefficients C_D, C_L, C_{DB} are presented in Fig. 40. The processing of the results showed that the drag decrease effect was 1.3 % in the first case and 6.1 % at the second switching on of the discharge. Non-proportional change of the effect to the level of the power certificates, probably, about a non-effective discharge use in the first case. The photographs of a flow over the model without discharge and at the discharge

presence are given in Fig. 41 (*a* -without discharge, *b* - with discharge, N ≈ .34 kW, *c* - also with discharge, N ≈ .6 kW).

In run 1322, the discharge had a larger time of burning that one could surely receive the steady regime at the bigger value of the discharge current (I_d ≈ 3.9 A) than in run 1321. The results of processing of the balance reading for this run are shown in Fig. 42. In this case, the initial value of C_D was .128 and the maximal value of the drag decrease effect equaled 7.8 % at the discharge power . 9 kW. Tepler photograph of a flow over the model at the discharge presence is given in Fig. 43. (For runs 1321 and 1322, only Tepler photographs were obtained). The photograph in Fig. 44 gives the model B2 state image after runs 1321 and 1322.

Model C

The results of processing of the balance reading for this model in runs 1302 and 1311 are presented in Fig.45. One can see that the value of C_D obtained in the different runs coincided satisfactory and equaled about .095.It was less than any minimal value of the coefficient C_D for other models with the working plasma generators that were investigated in these experiments. In Fig. 46, the photograph of a flow around this model is given.

Some results of the spectroscopic measurements

As it was pointed out above, the spectroscopic measurements of the gas (rotation) and vibration temperatures were carried out by MSU in all the runs. However, only in some runs , spectrums obtained satisfied requirements of reliable determination of these temperatures. Typical results of the spectrum processing were presented by MSU for this report. In particular, in Fig. 47,*a*, the longitudinal distribution of gas temperature behind the lateral electrodes downstream in the discharges at run 1314 are shown. The curve 1 corresponds the regime when the amplitude of AC current was 1.05 A. The curve 2 was obtained at I_d equaled 1.42 A. For the curve 3 this amplitude was about 3.4 A. One can see that the gas temperature increased with the current gain. Near the lateral electrodes, it was in the range of 900 - 1,800 K and fell at the displacement downstream.

In Fig. 47,*b*, the distribution of this temperature between the needle and the lateral electrodes and also behind the last in run 1321 are presented. The amplitude of AC current was .75 A for the curve 1 and 2.6 A for the curve 2. The region where the temperature was practically constant corresponds to the interelectrode gap.

The processing of spectrums in the both runs showed that, the vibration temperature achieved about 10,000 K and fell to 5,000 - 6,000 K on the distance of

1.5 cm downstream the lateral electrodes, i.e. a strong non-equilibrium of translation and vibration temperatures took place in the discharge. This circumstance has to take into account at the theoretical analysis of the effects of the discharges influence on a flow over a body.

Comparison of the drag decrease effects with the results of previous experiments

It is of interest to compare the results obtained in this study for the model A at the plasma generator supply from the capacity storage and the results attained in the previous work [7] for the model with like geometry. The sketch of the model that was investigated in those experiments is presented in Fig. 48. It had the conical nose part of caprolon with the half angle of the cone equal 15^0 and semispherical bluntness. The radius of the bluntness was 1 cm. The cylindrical part of the needle had the diameter of 4 mm. The central conic electrode of the needle was made of copper and had the half angle about 10^0. There was a metal ring of about 7mm - diameter on the ceramic tube surface of the needle for relief of the discharge ignition. The discharge gap of this model had a more length than that for the model A. For the electric supply of the plasma generator, the combination of quasi-steady source of energy (the capacity storage) and the pulsed source of energy was used. The last source had a low power but high voltage that, probably, relieved the stable burning of the discharge. For this model, the effect of the drag decrease was obtained on the level 36 % at the power supplied to the discharge equal about 2.1 kW (see Fig. 49) and 18 % at the power about 1 kW i.e. the discharge influenced more effective on a flow over the model than for the model A. An important peculiarity of the discharge on the older model was that it burnt, in basic, between electrodes, in the separation zone ahead the bluntness (its boundary is showed schematically in Fig. 48 by a dashed line), and was drifted weakly downstream. We suppose the basic reasons of such difference of the results lie in that, the lateral electrodes of the older model were arranged nearer to the separation zone, than that for the model A and also because of the peculiarities of the electric supply of the discharge.

SUMMARY

The results of this investigation confirmed the opinion of the aerodynamists of TsAGI that the drag reduction effect must decrease with improvement of the aerodynamic form of the model. The study showed that the value of this effect depended essentially on the type of the plasma generator supply. The basic results obtained in these experiments are given in the following table:

Type of the model	A (semispherical bluntness with the needle)		B (conical bluntness with the needle)	C close to optimal form
Type of current	DC	AC	AC	-
C_{Di}	.196	.194	.128	.095
$(\Delta C_D/C_{Di})_{max}$,%	13.3	11.3	7.8	-
C_{Dmin}	.170	.172	.118	.095

Here, C_{Di} is the initial value of C_D before the discharge, C_{Dmin} is the minimum value of this coefficient (at the discharge for the models A and B), $(\Delta C_D/C_{Di})_{max}$ is the maximum value of the drag decrease effect at the discharge ignition.

The energy expenditure reduction at AC discharge use is the interesting and important result of this investigation but it needs in the additional experimental confirmation in future.

The results obtained in this study show that at present we have the stage of accumulation of information about the electric discharge influence on the aerodynamic drag. And so far, the picture is far from completion. Therefore it is desirable to go on the fundamental experiments in this field of research.

REFERENCES

1.Klimov A.I., Koblov A.M., Mishin G.I. Propagation of shock waves in a glow disharge plasma. // Pis'ma v Zhurnal Teknicheskoi Fiziki. 1982. V.8,No7, pp.344-349 (in Russian).

2.Mishin G., Klimov A.I., Gridin A.Yu. Measurements of pressure and density in shock waves in a gas discharge plasma. // Pis'ma v Zhurnal Tekhnicheskoi Fisiki. 1991. V.17, No 16, pp. 84-89 (in Russian).

3.Klimov A.I., Mishin G.I., Fedotov A.B., et. al. Propagation of shock wavesin non stationary glow discharge. // Pis'ma v Zhurnal Tekhnicheskoi Fiziki. 1989. V.15, No20, pp. 31-36 (in Russian).

4.Ganguly B.N., Bletzinger P., Shock wave dispersion in non-equilibrium plasmas. // AIAA 96-

5.Pankova M.B., Bocharov V.V. «Possibilities of plasma aerodynamics» // Samolet, 1995,No 1, pp 15 - 20.

6. Gordeev V.P., Krasilnikov A.V., Lagutin V.I, Otmennikov V.N. Experimental study of possibility of the drag reduction at supersonic speeds with use of plasma technology Mechanics of fluid and gas, 1996, No 2, pp 177-182.

7.Gridin A.U., Efimov B.G., Zabrodin A.V., Klimov A.I., Kuznetsov Yu.E., Skvortsov V.V., and etc. Numerical and experimental investigation of supersonic flow around blunt body with the

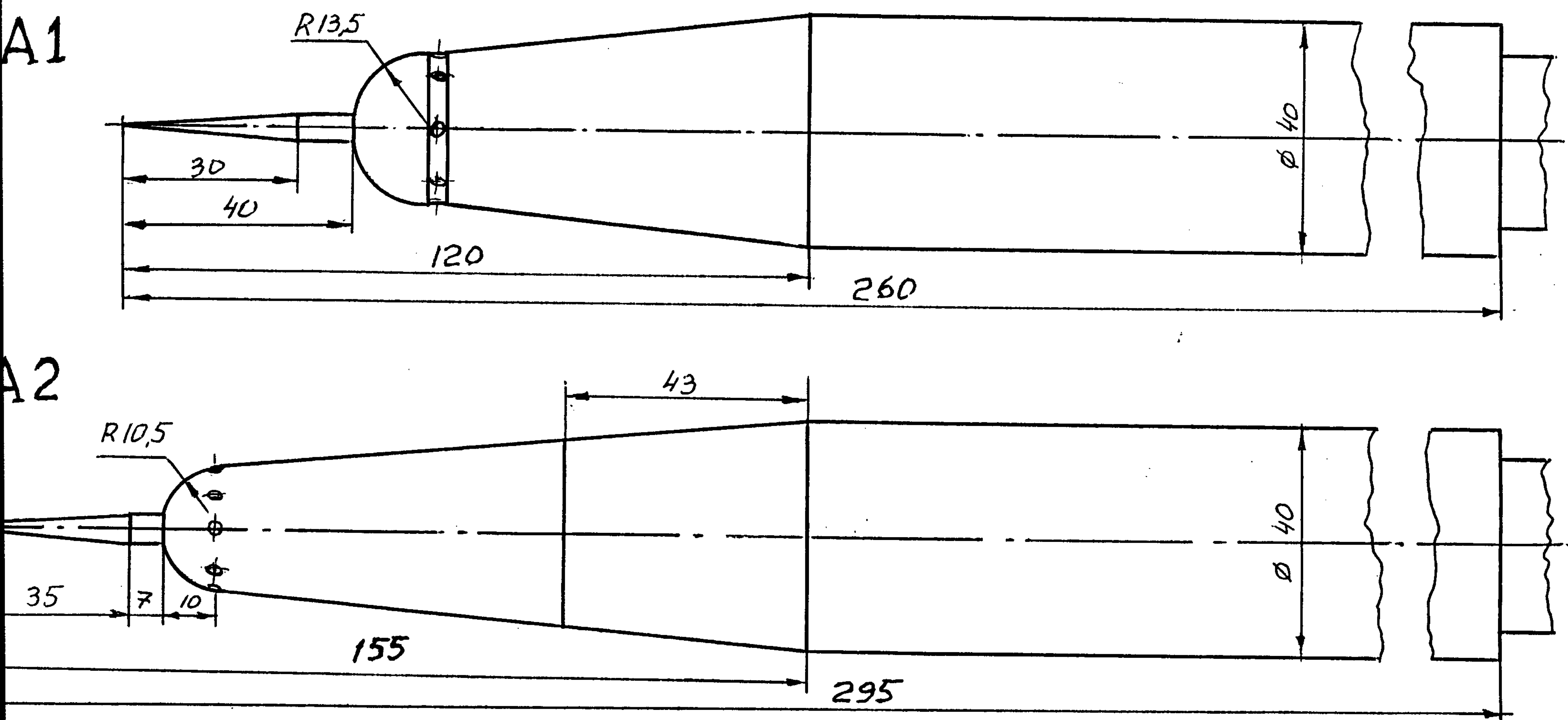


Fig.1

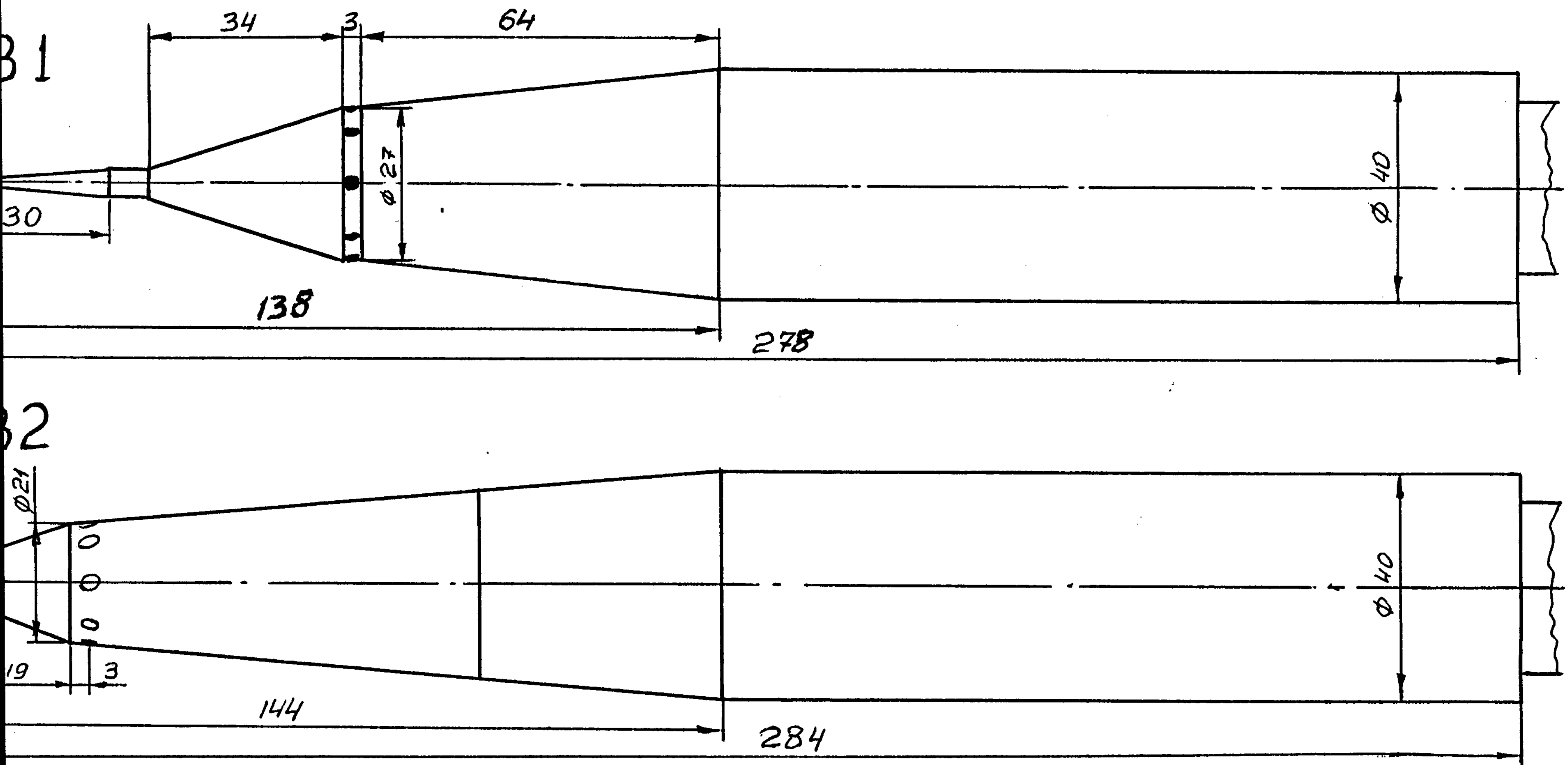


Fig.2

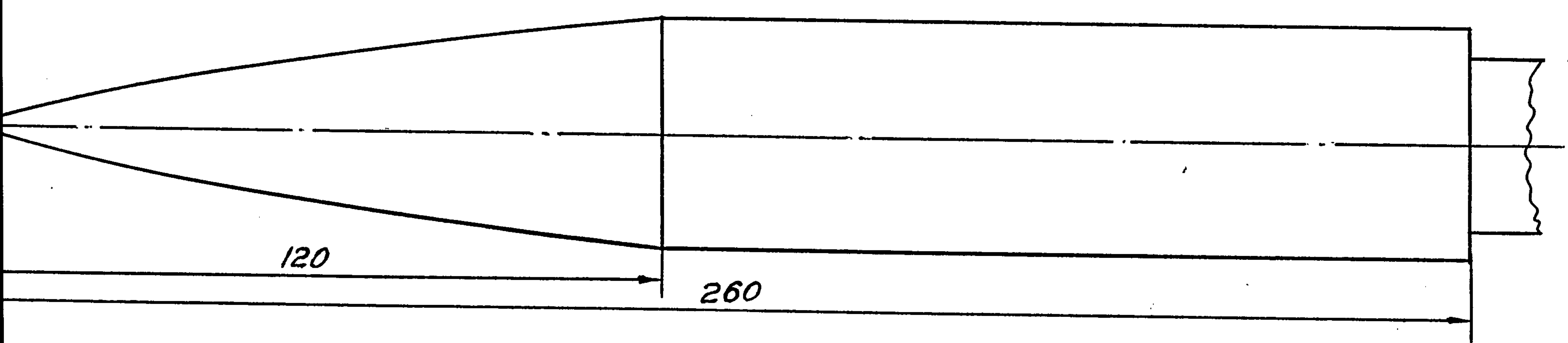


Fig.3

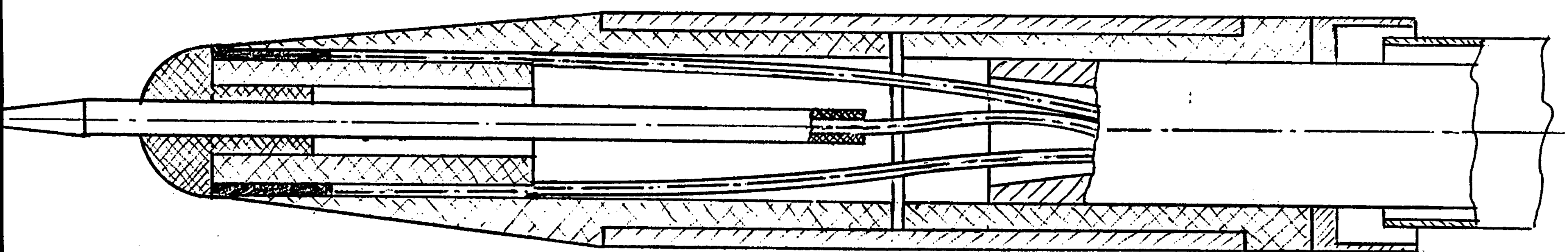


Fig.4

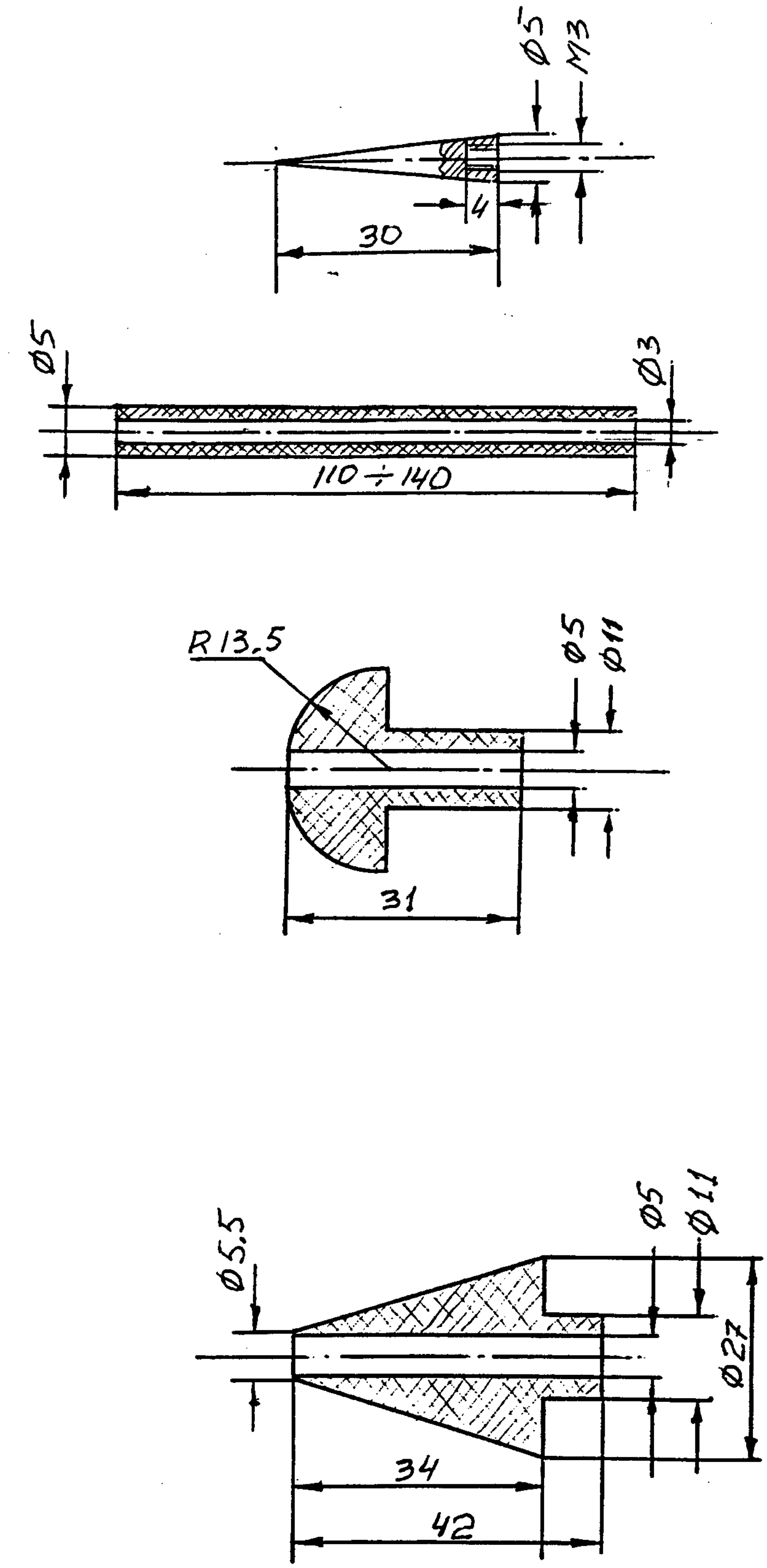


Fig.5

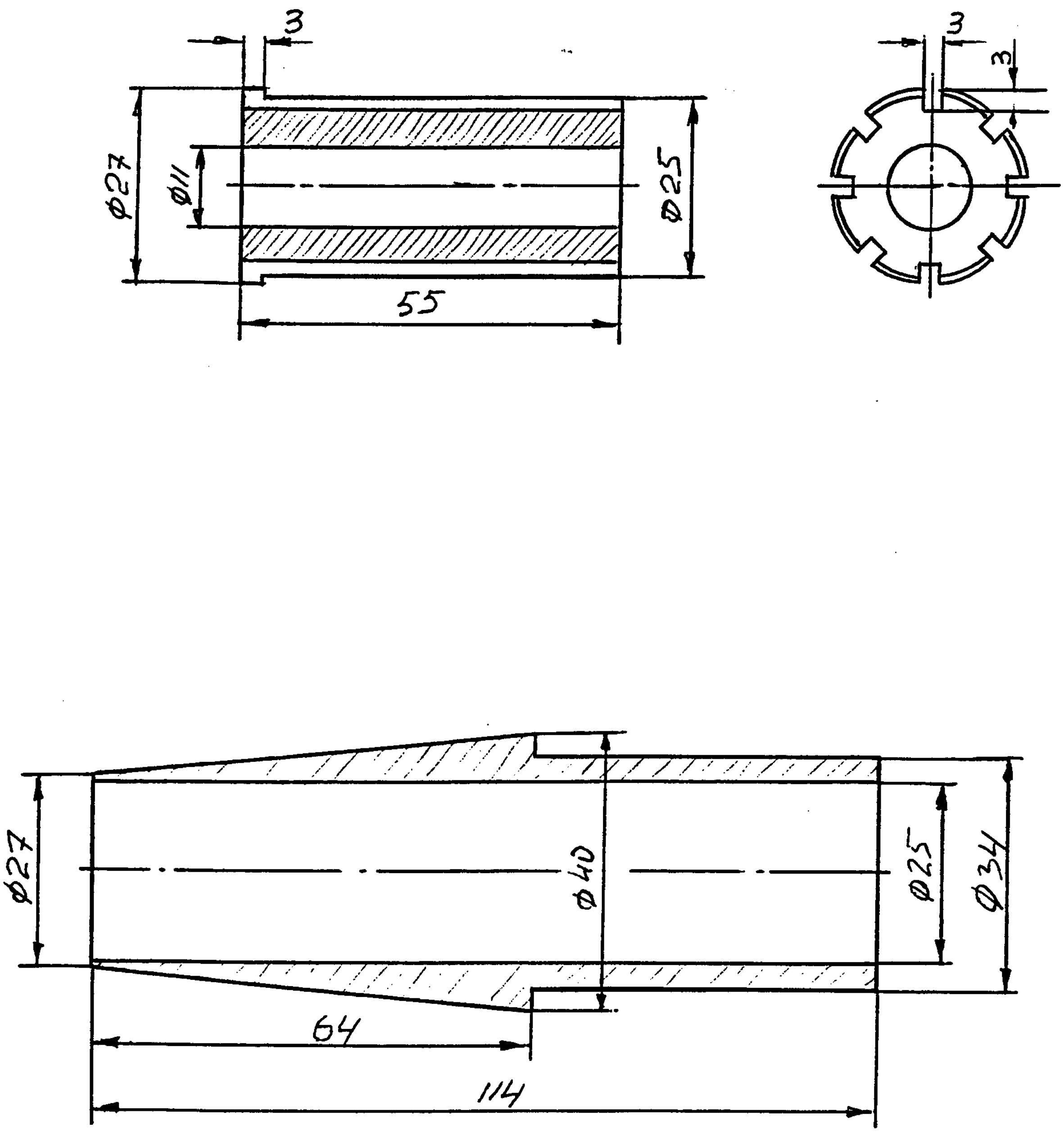


Fig.5

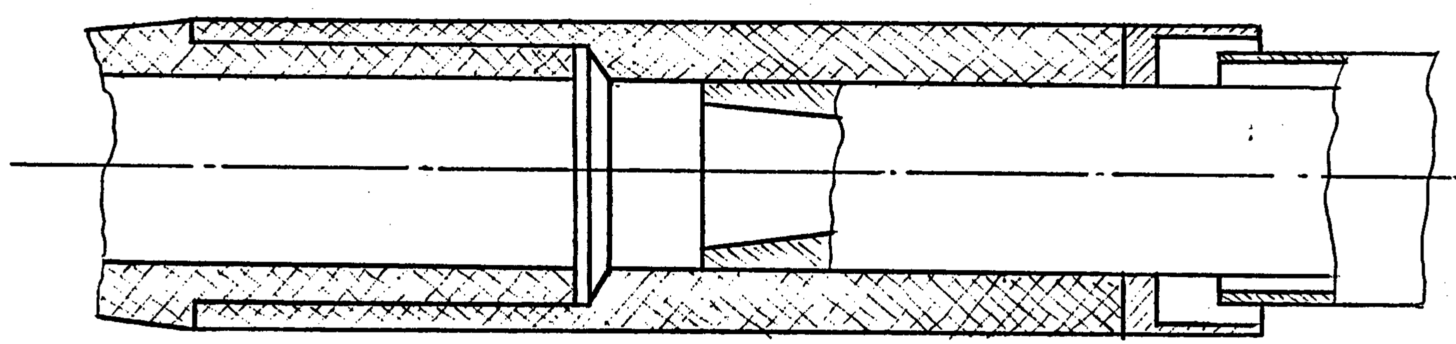


Fig.7

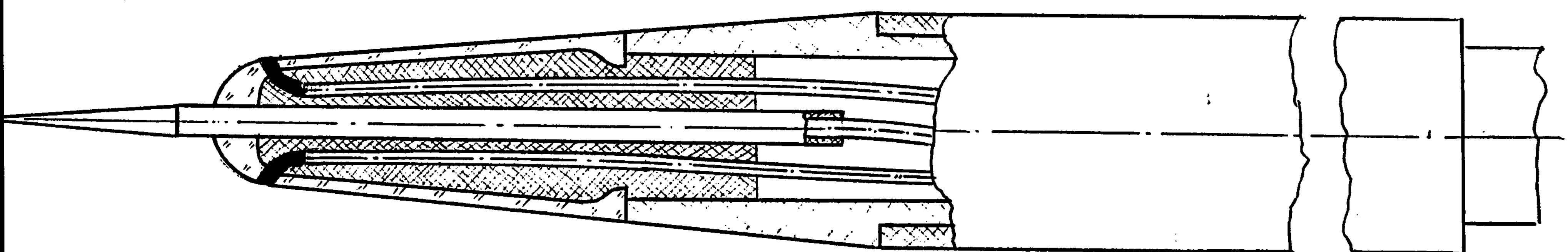


Fig.8

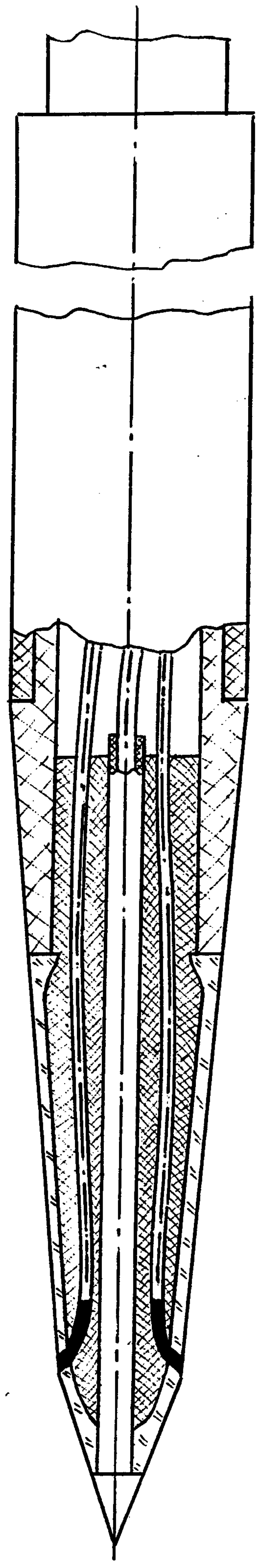
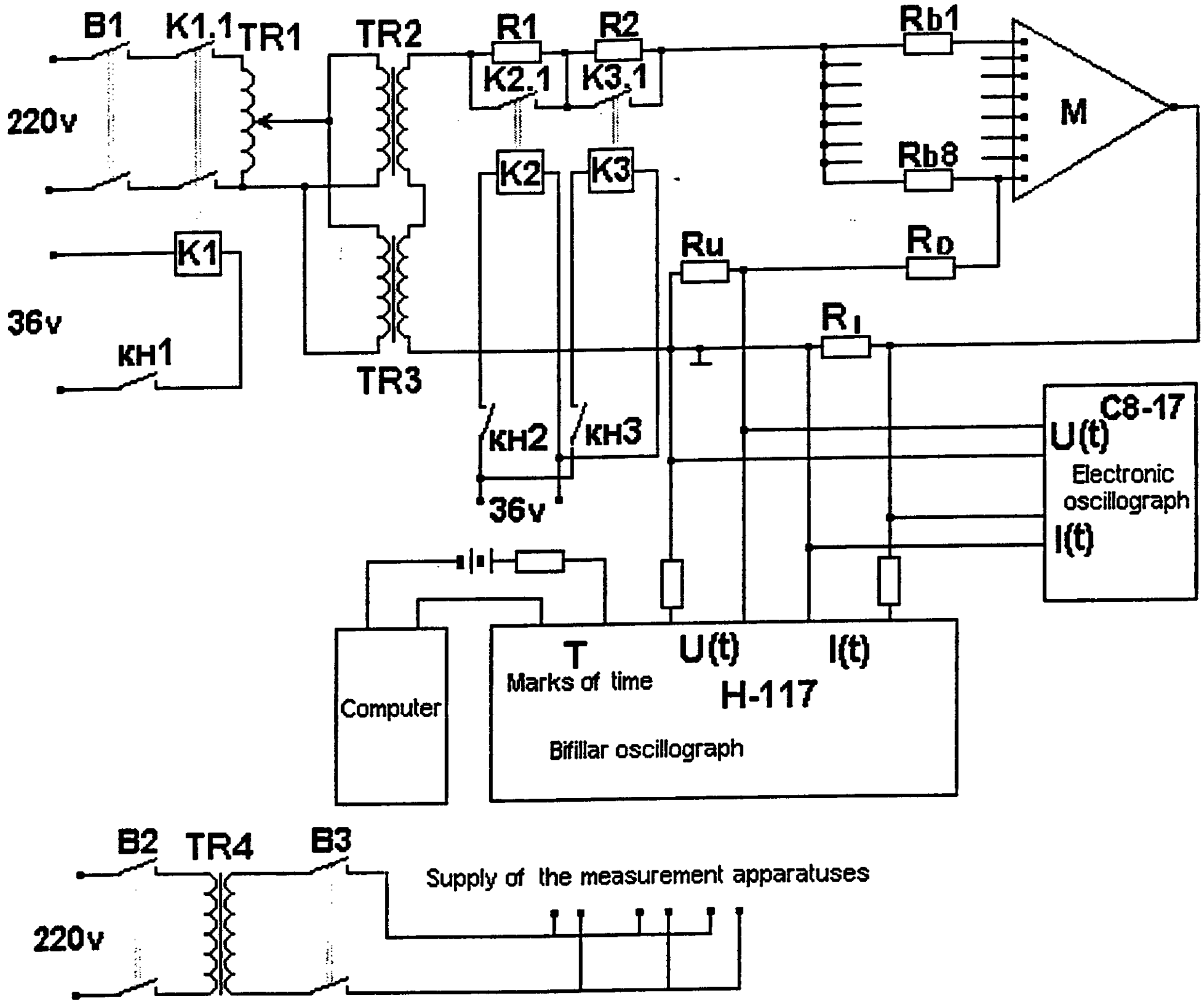


Fig.9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TR2
R1
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Rb1
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Ru
RD
36v
KH1
RI
TR3
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36v
C8-17
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Supply of the measurement apparatuses

Fig.10

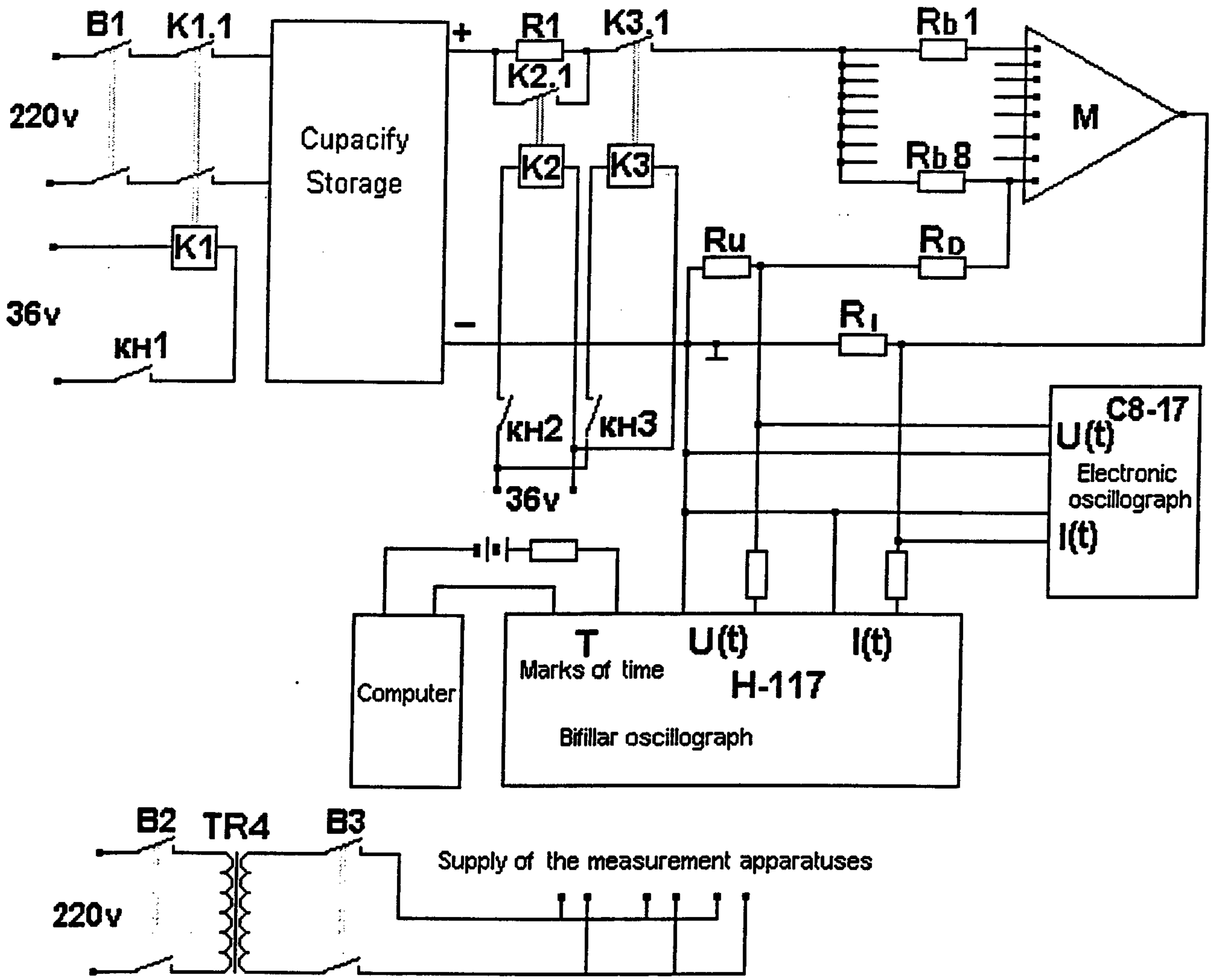
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Fig.11

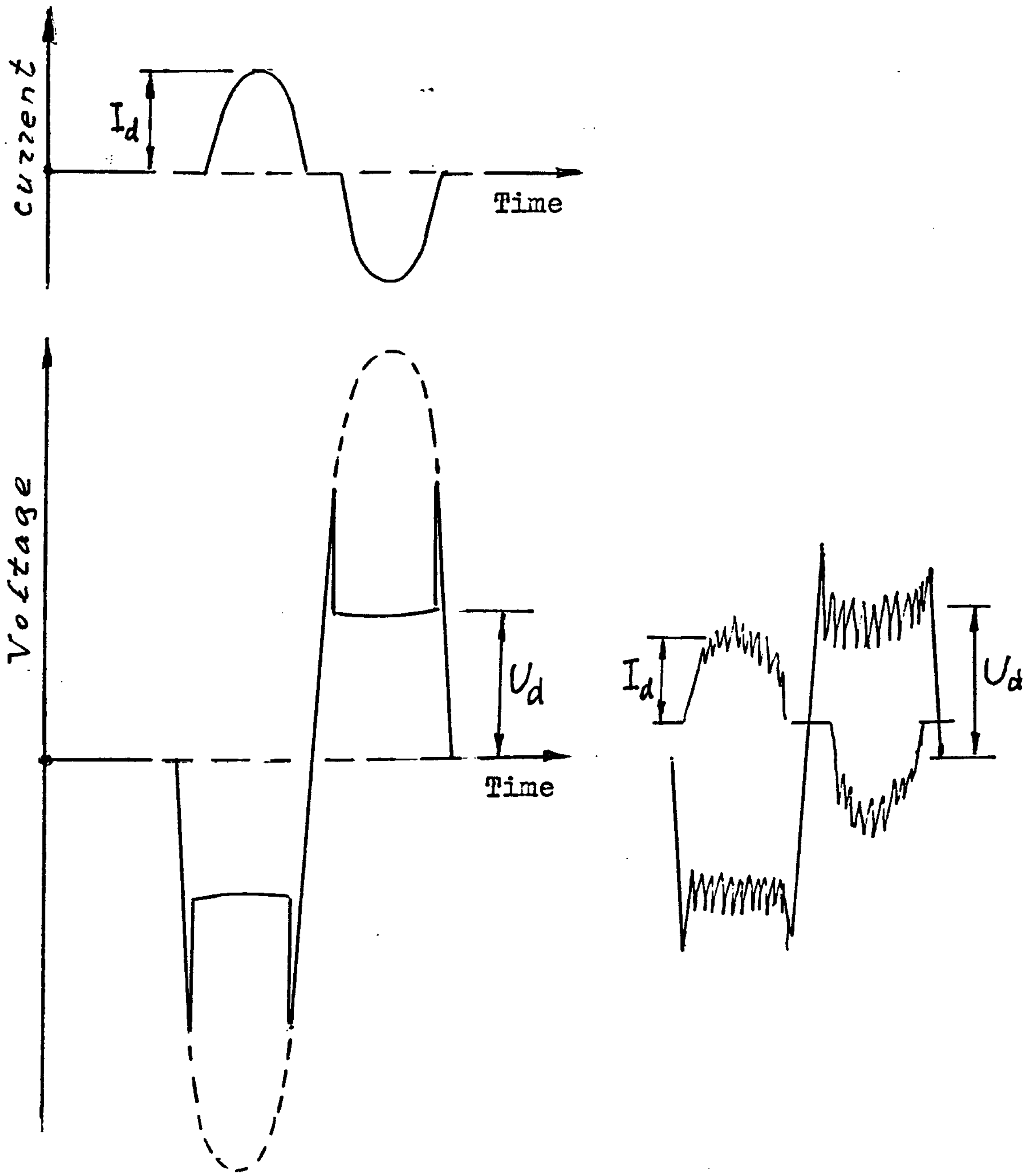
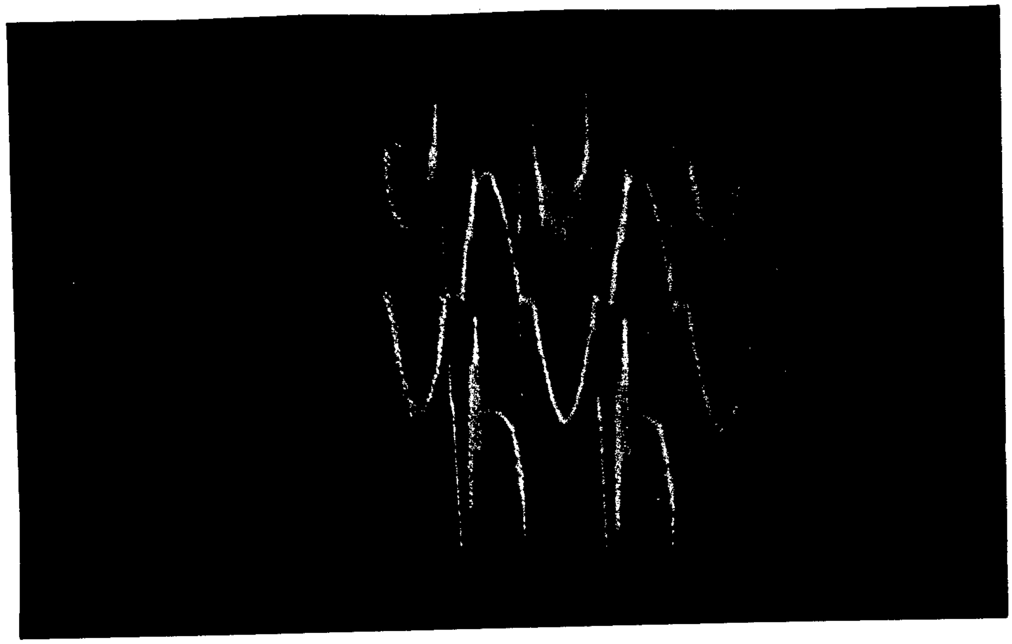


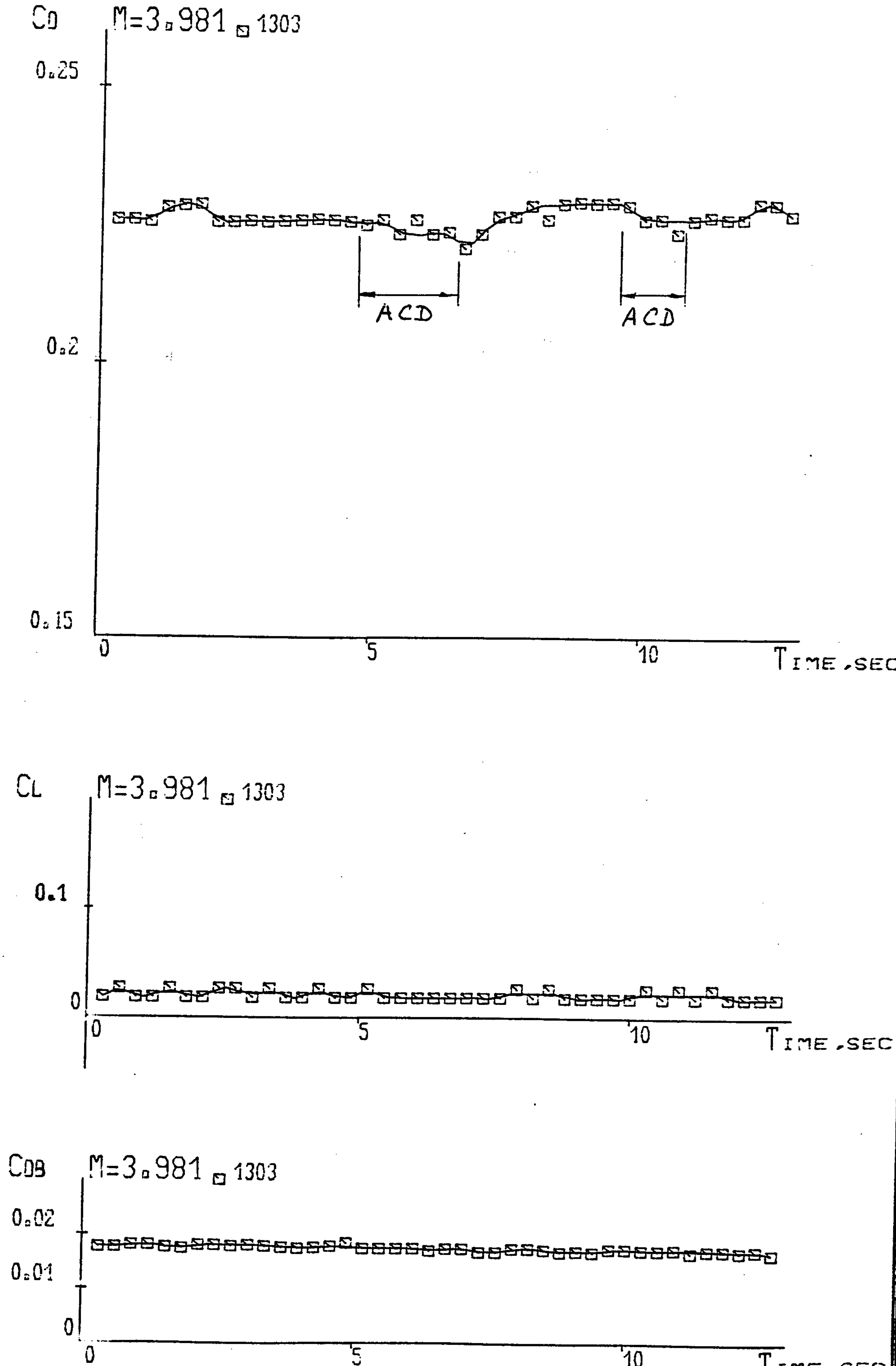
Fig.12



A

B

Fig.13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ACD
ACD
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TIME,SEC
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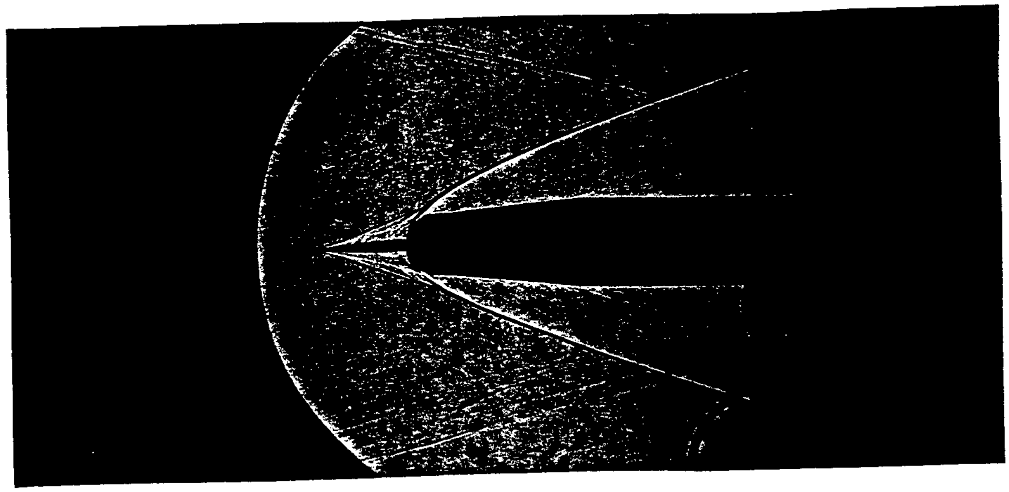
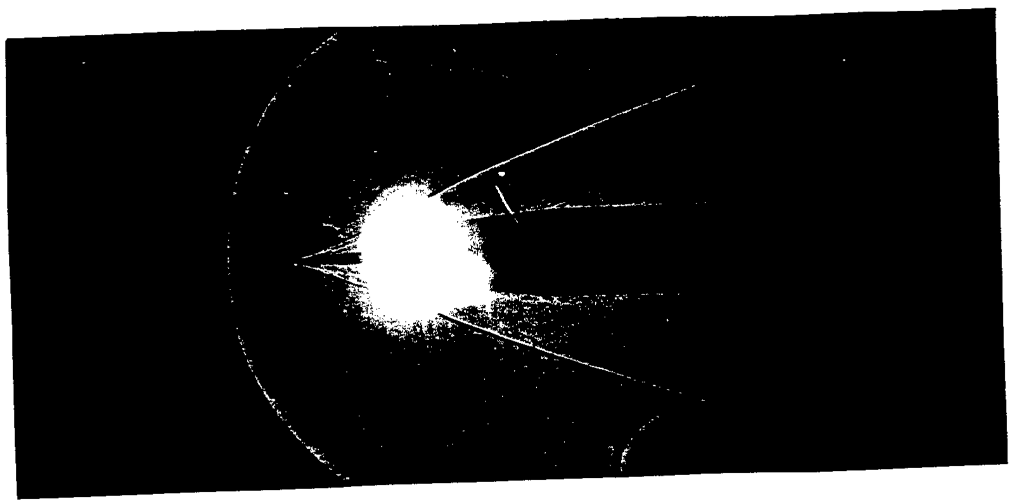
TIME,SEC

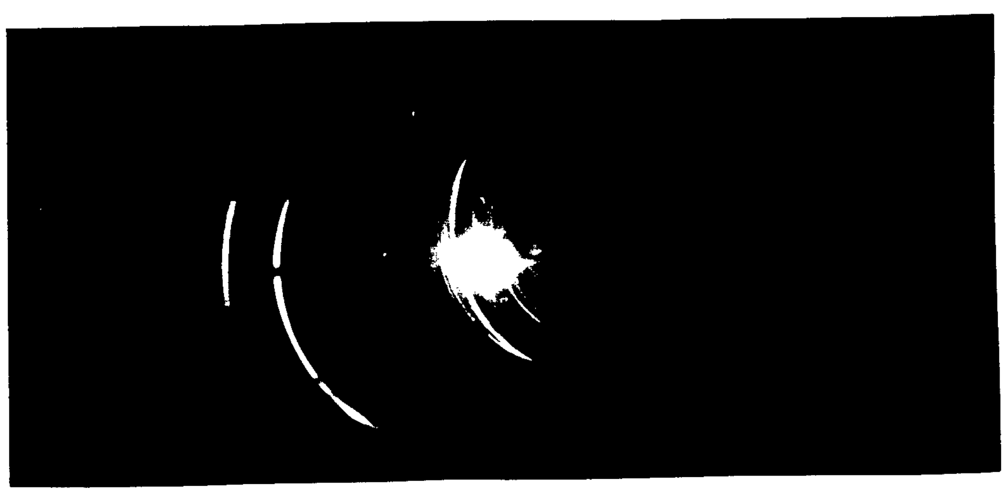
Fig.14



A

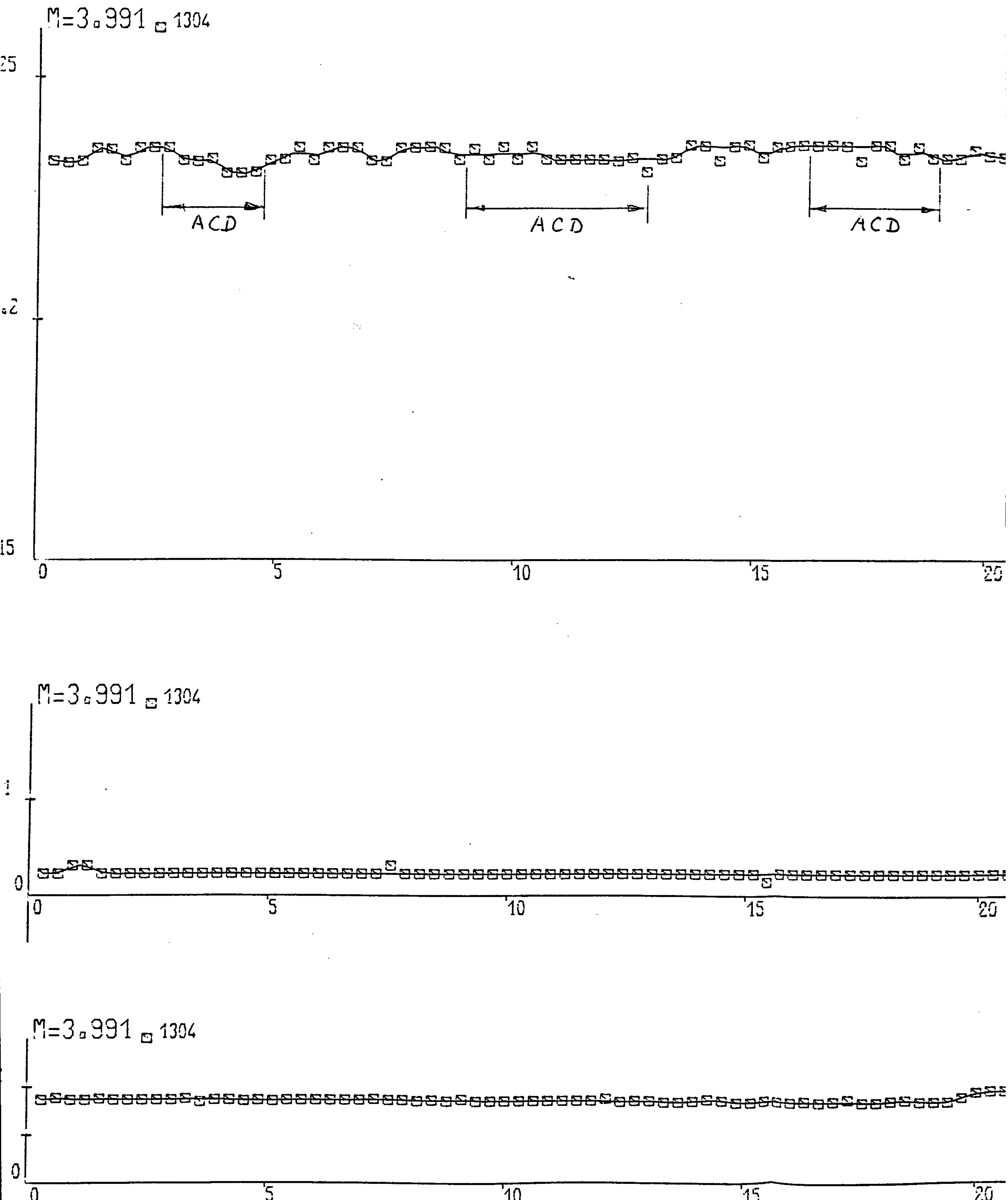


B



C

Fig.15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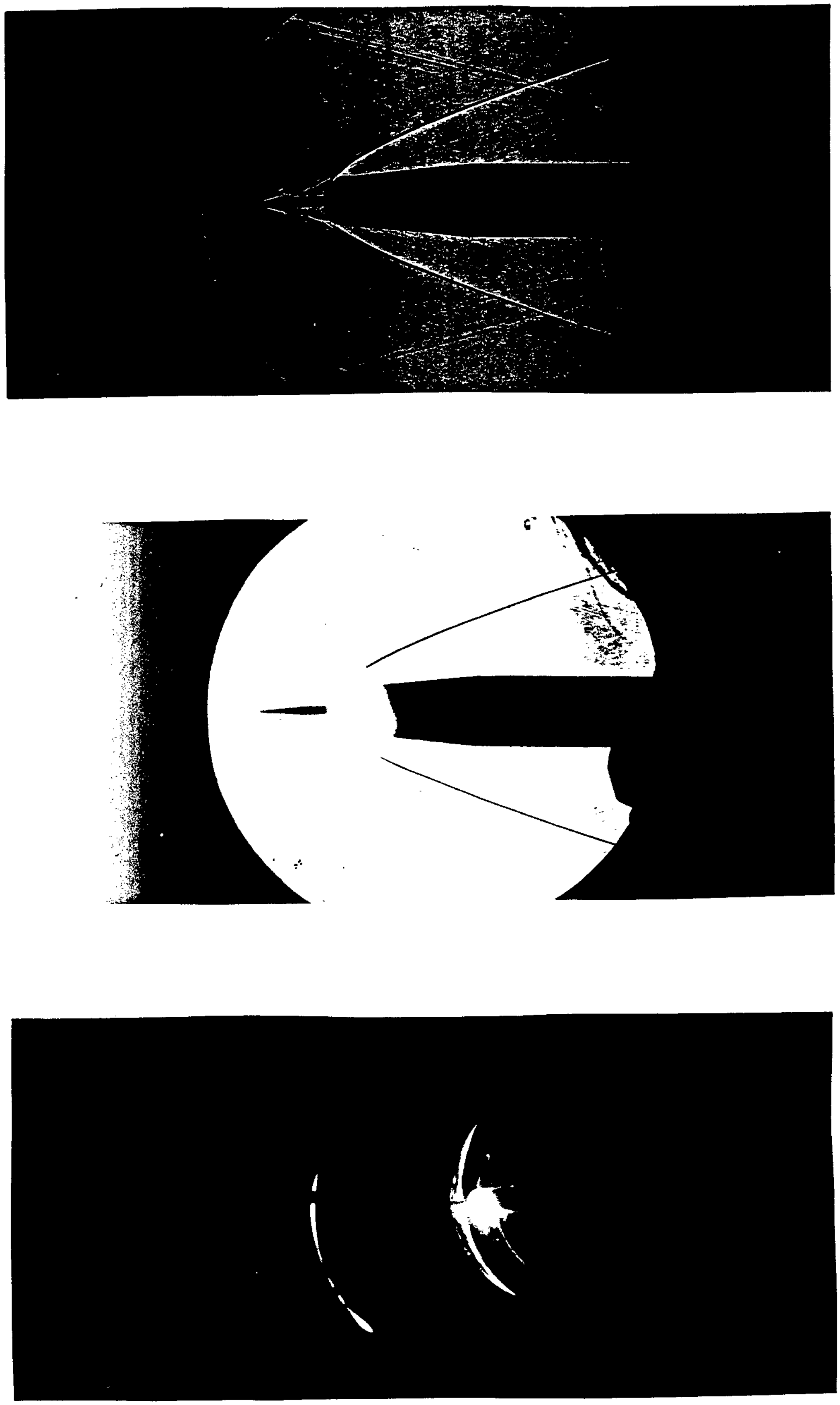
20

Fig.16

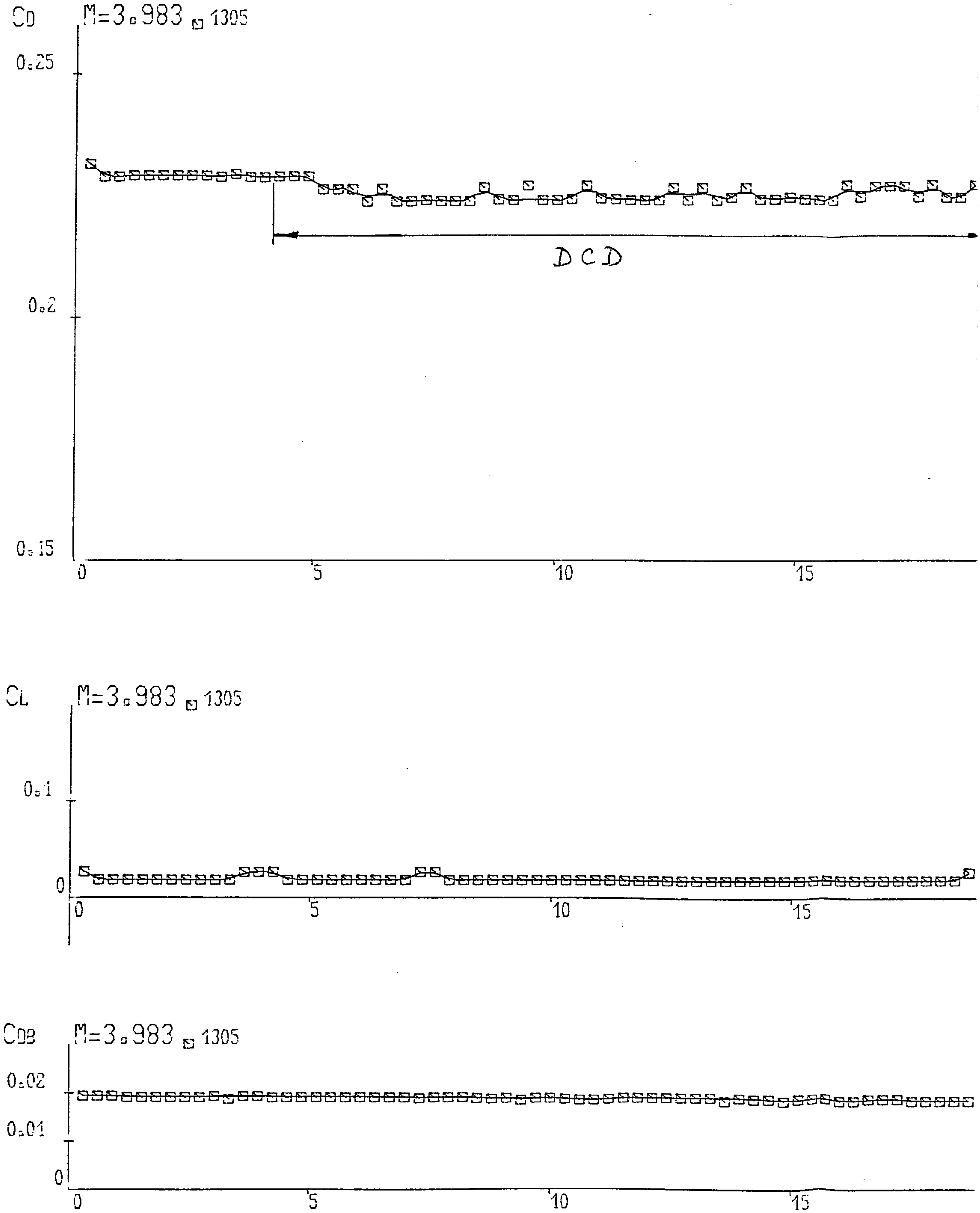


A

B

C

Fig.17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0.2
0.15
DCD
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5
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15
CL
M=3.983 1305
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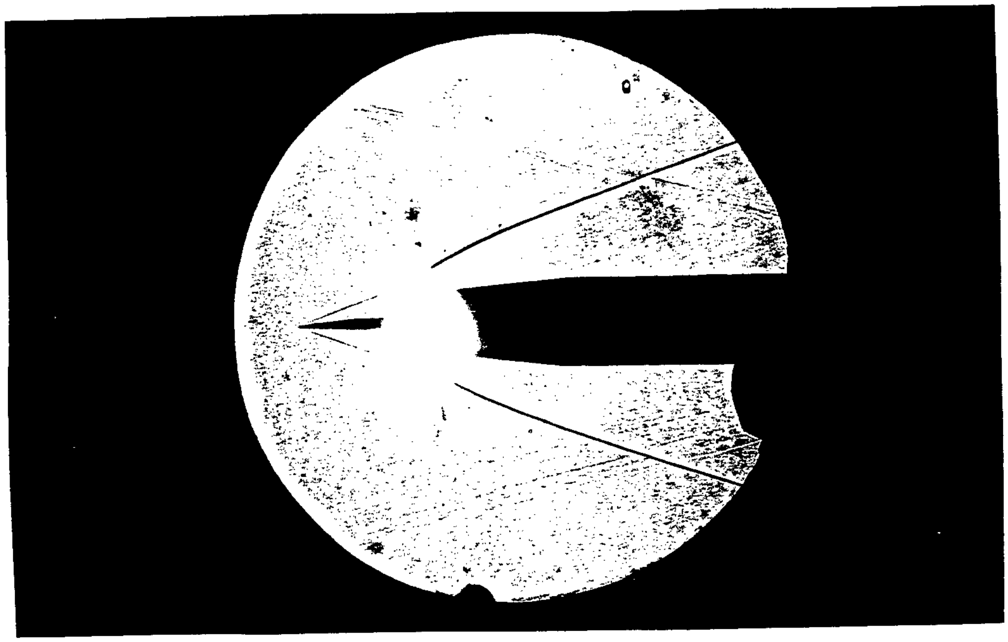
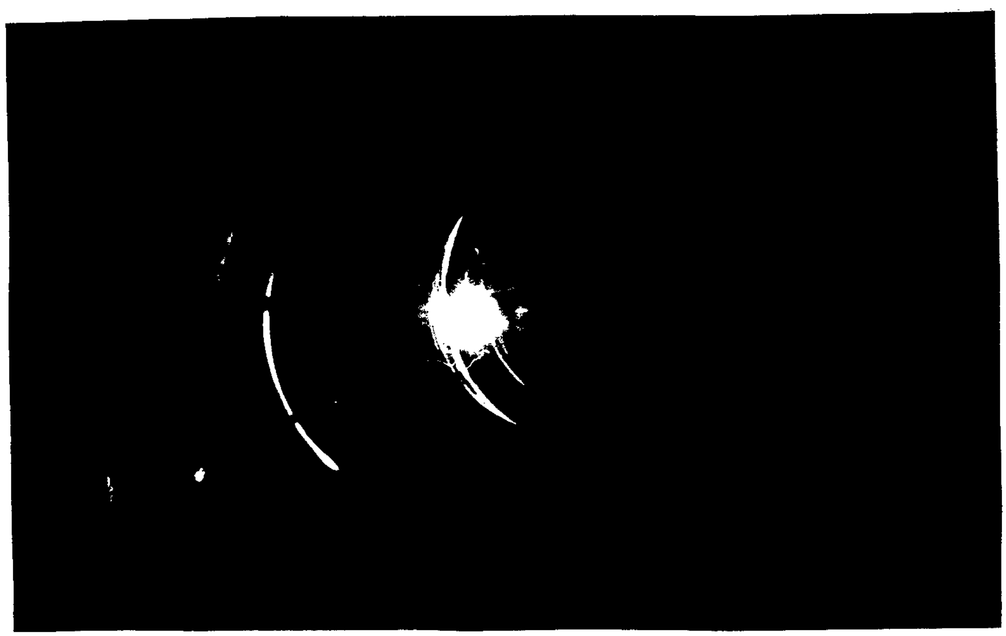
10
15
CDB
M=3.983 1305
0.02
0.01
0
0
5
10
15

Fig.18

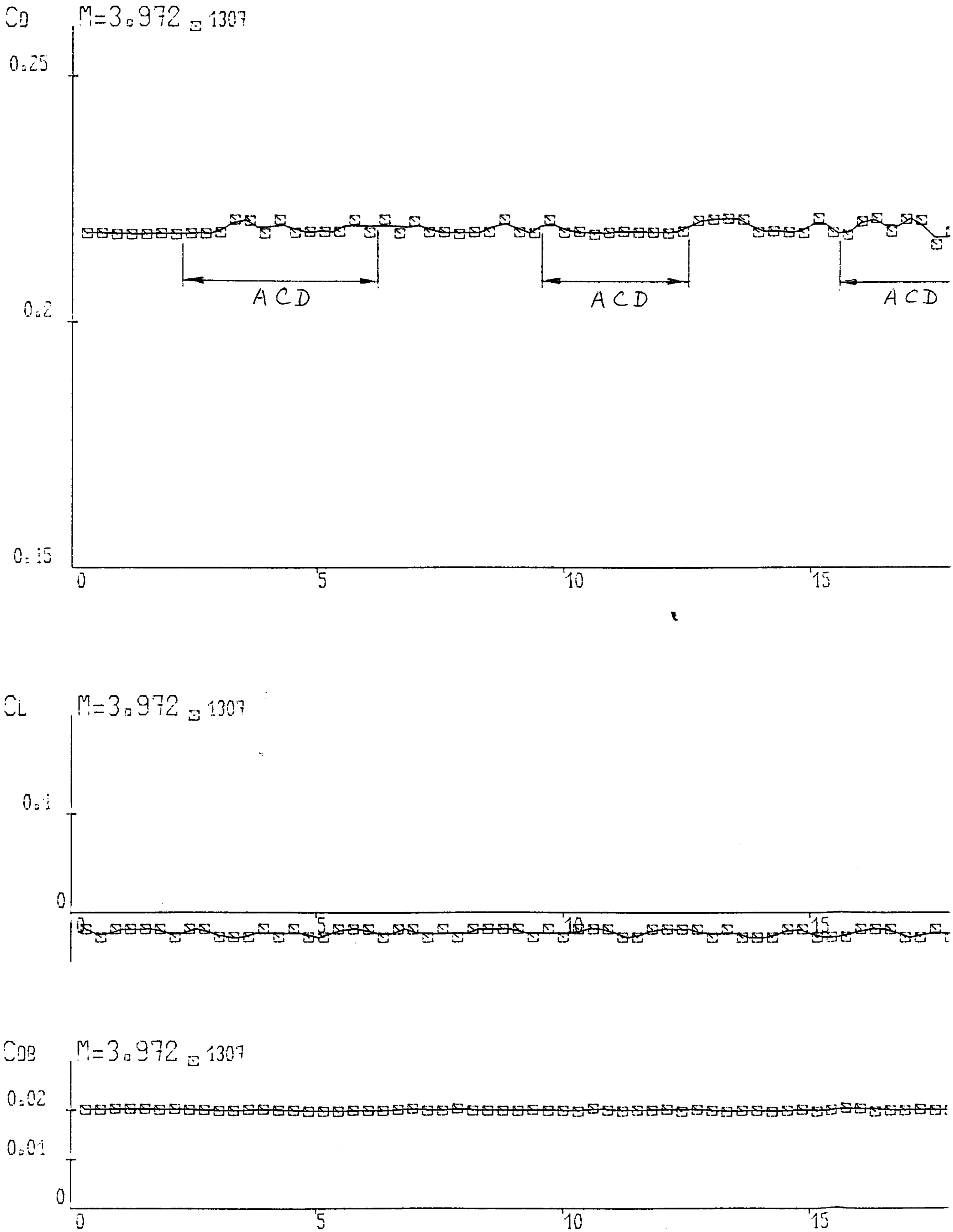


A



B

Fig.19



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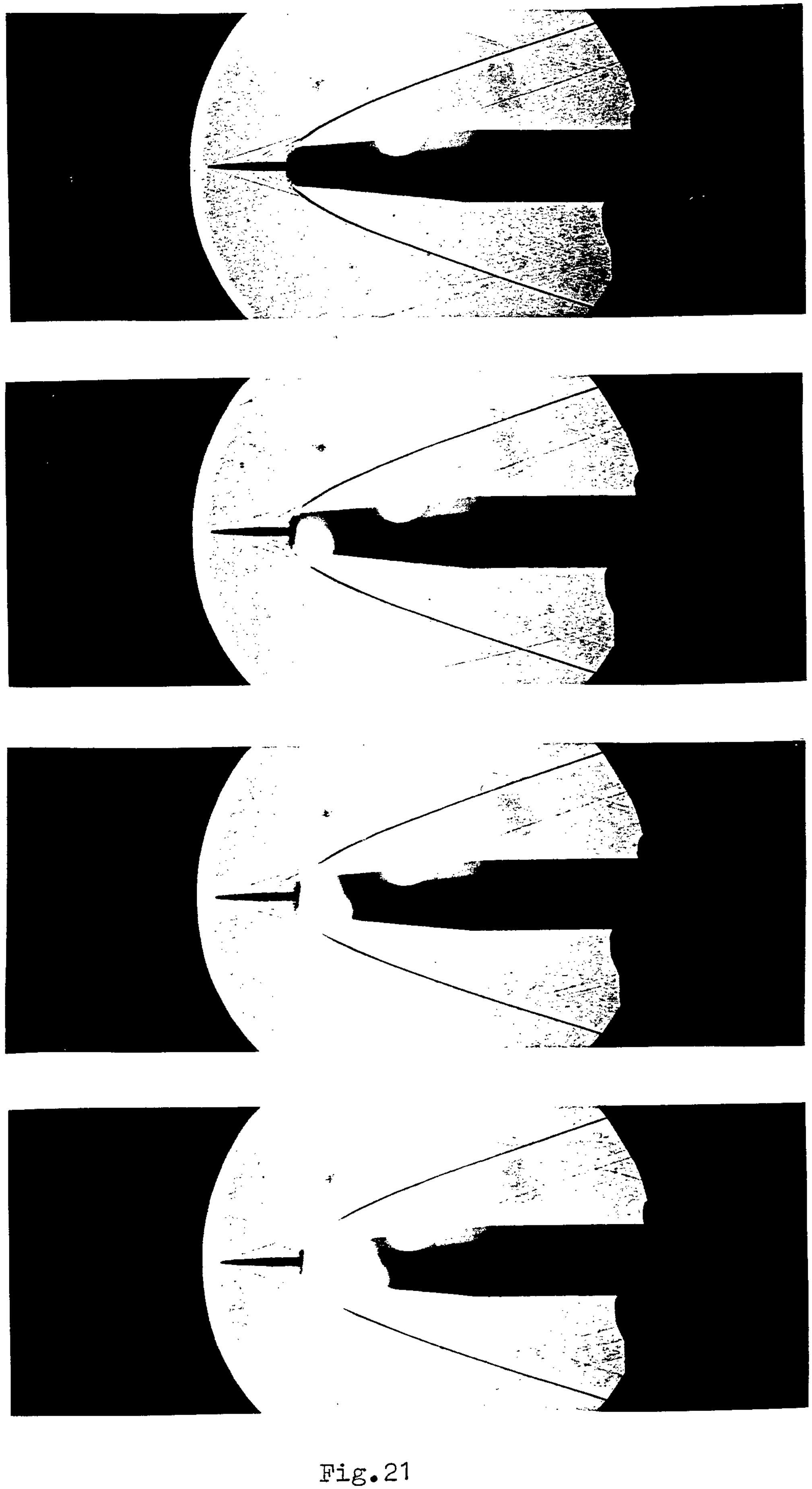
0.2
0.15
ACD
ACD
ACD
0
5
10
15
t
CL
M=3.972 1307
0.1
0
CDB
M=3.972 1307
0.02
0.01
0

Fig.20



A

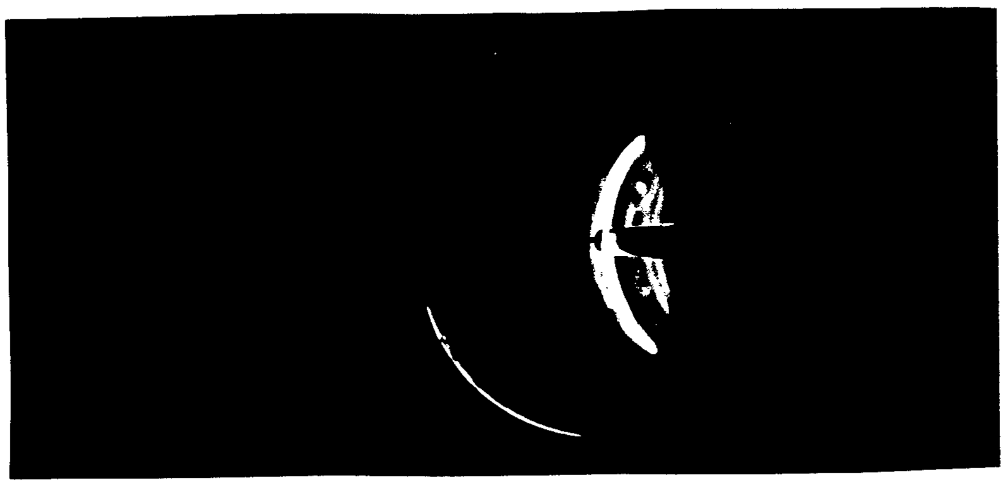
B

C

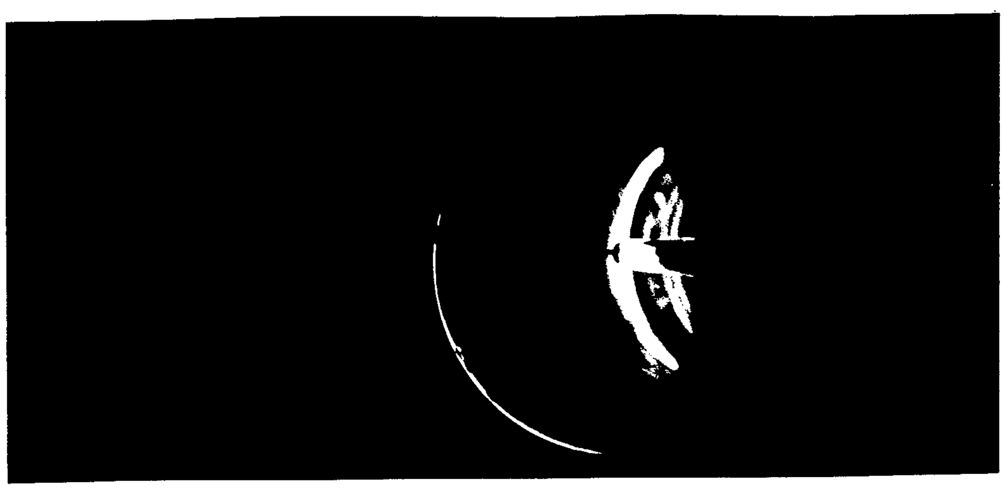
D

Fig.21

A



B



C

Fig.22

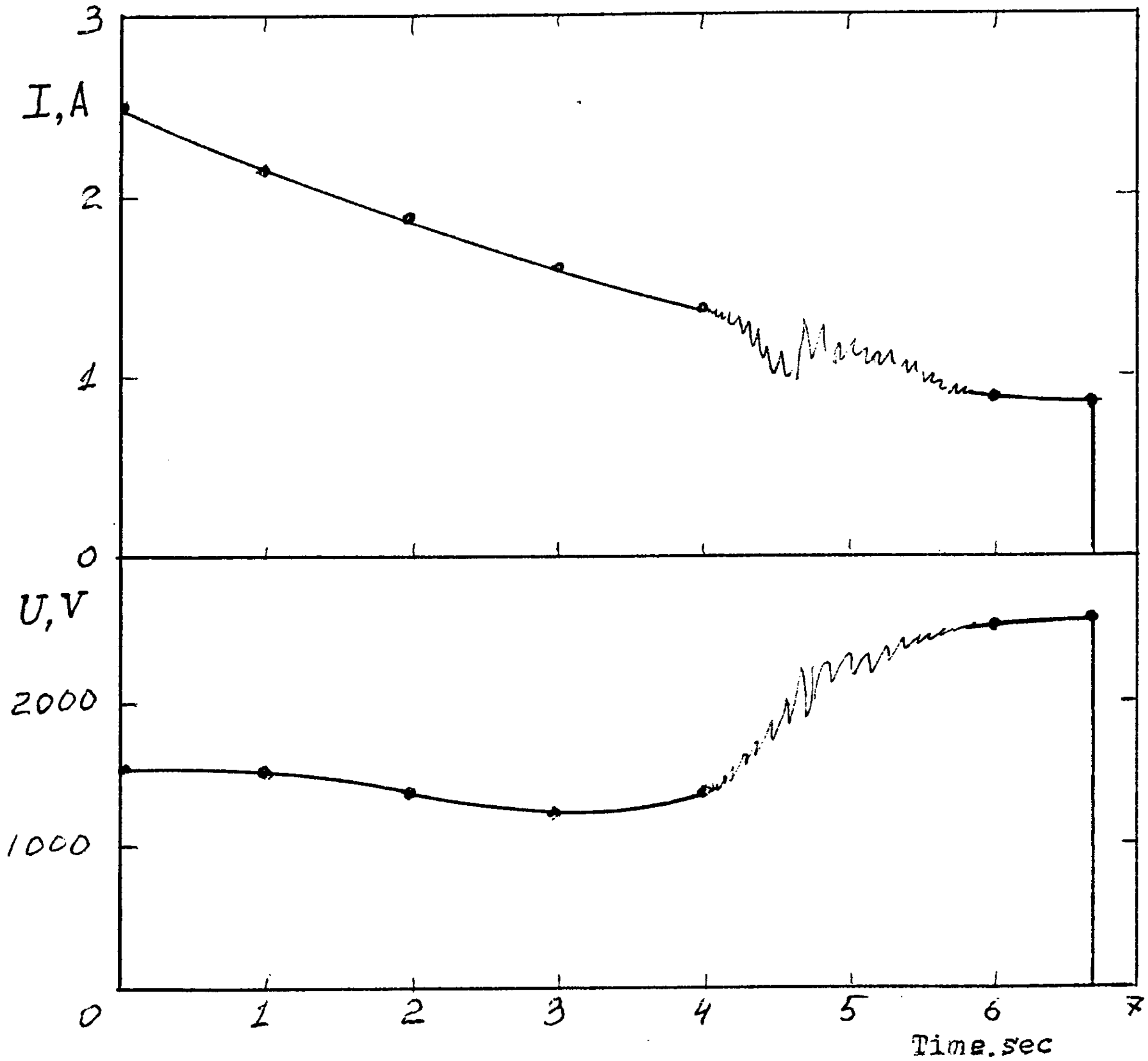
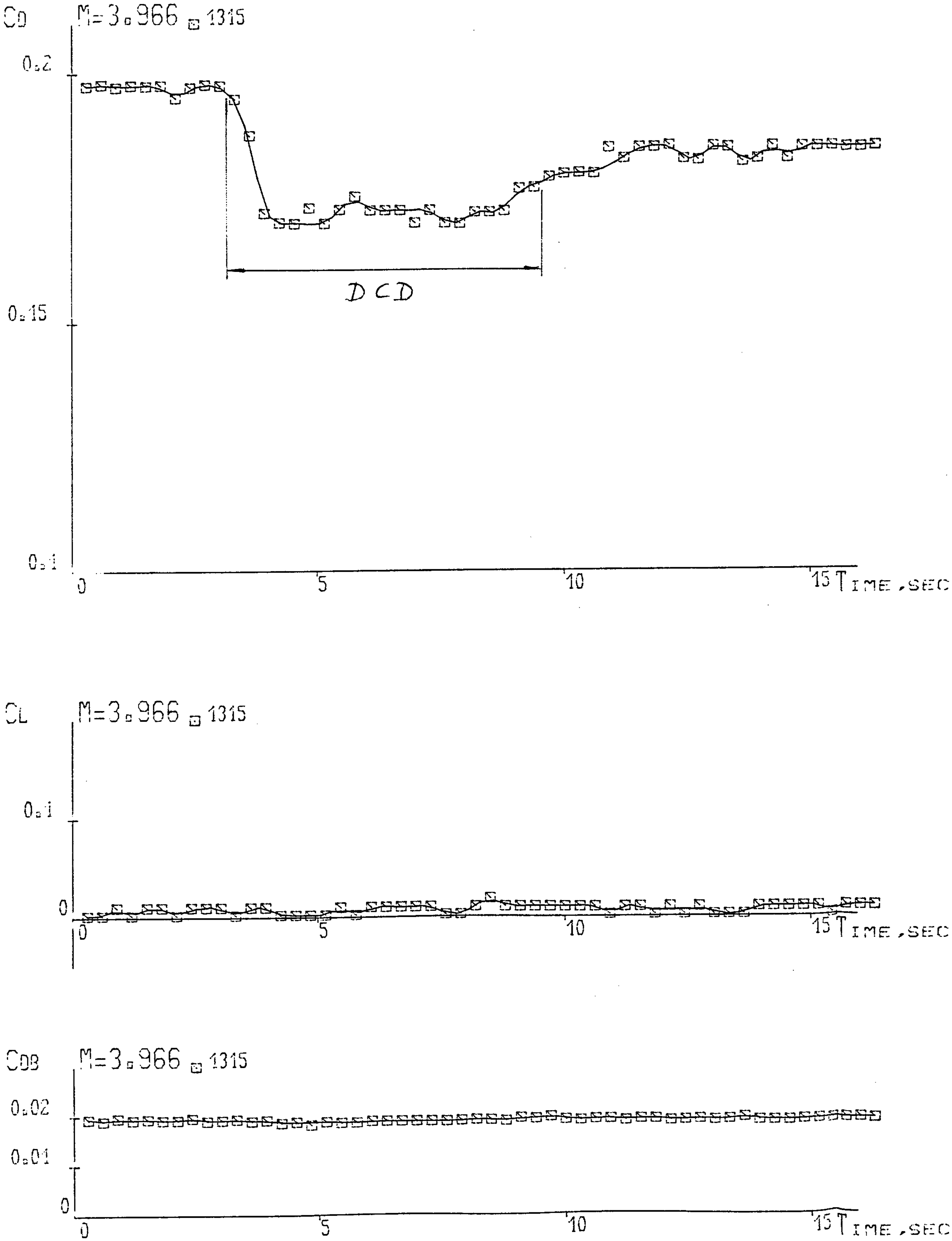


Fig.23

1315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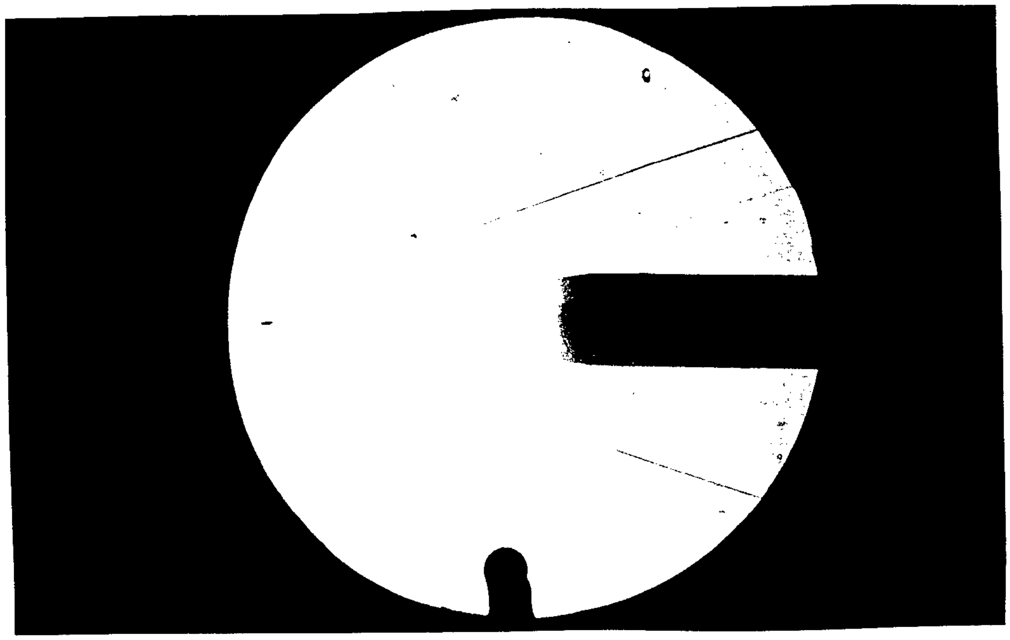
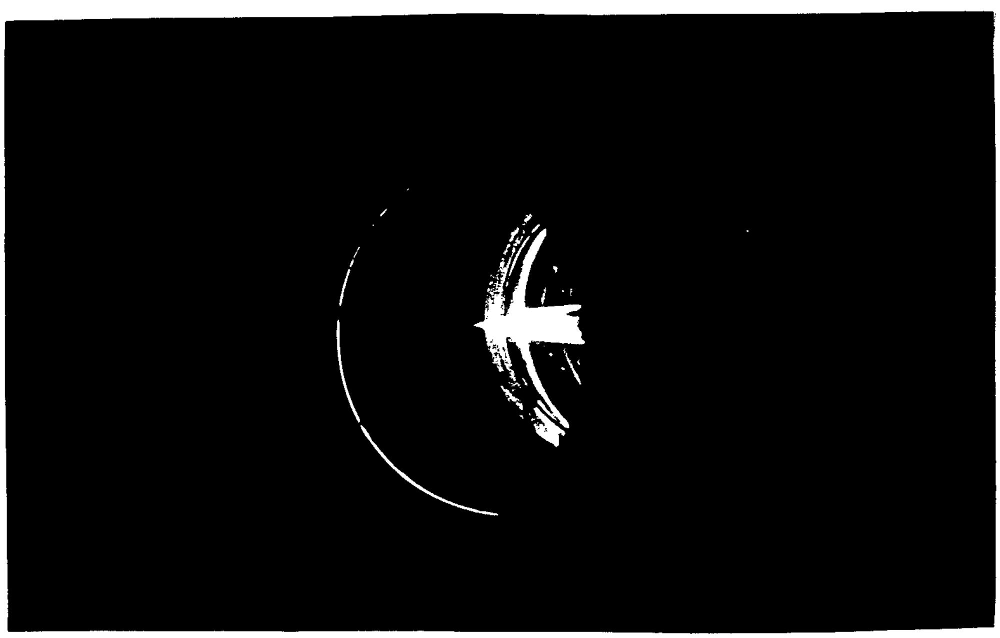
0.2
0.15
0.1
DCD
0
5
10
15 TIME, SEC
CL M=3.966 1315
0.1
0
0
5
10
15 TIME, SEC
CDB M=3.966 1315
0.02
0.01
0
0
5
10
15 TIME, SEC

Fig.24



A



B

Fig.25

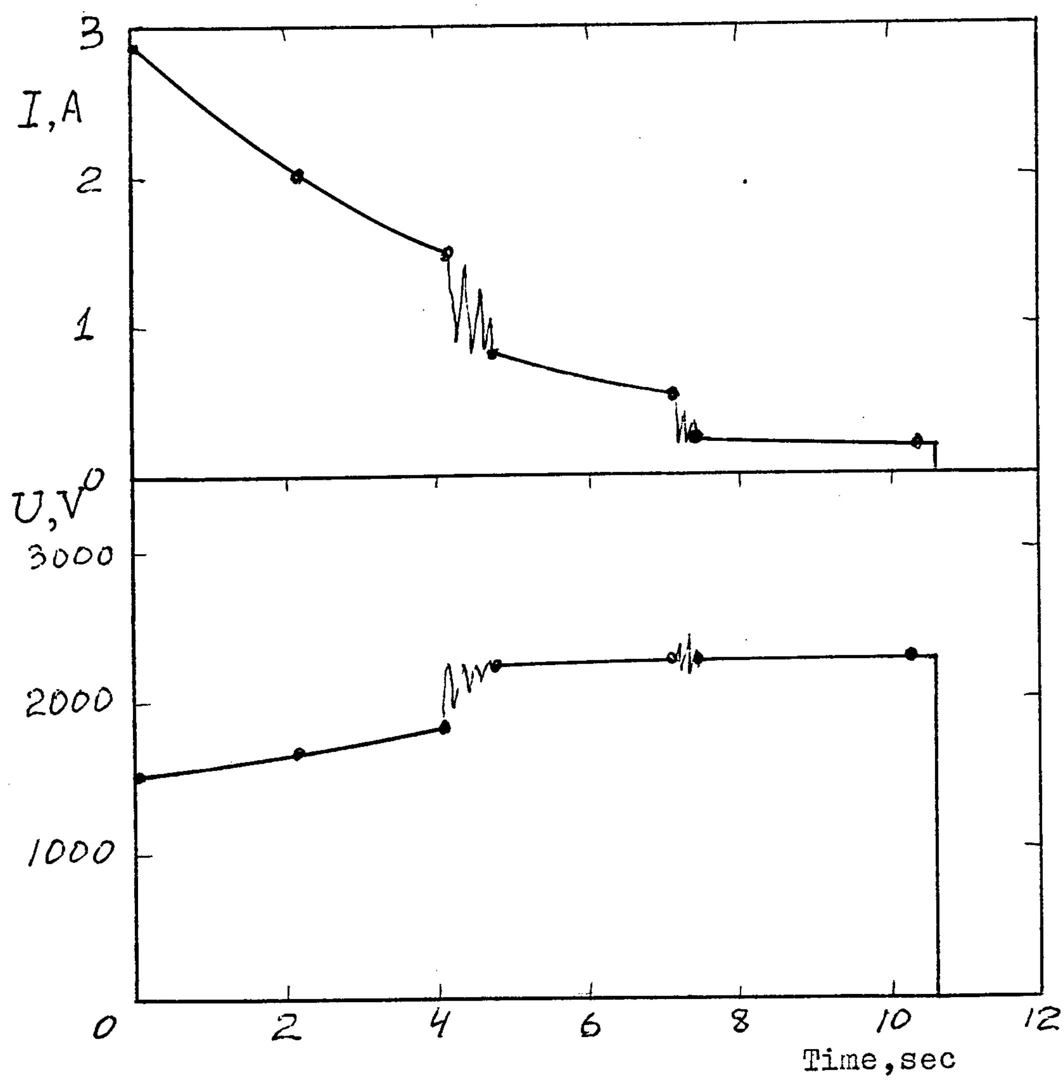
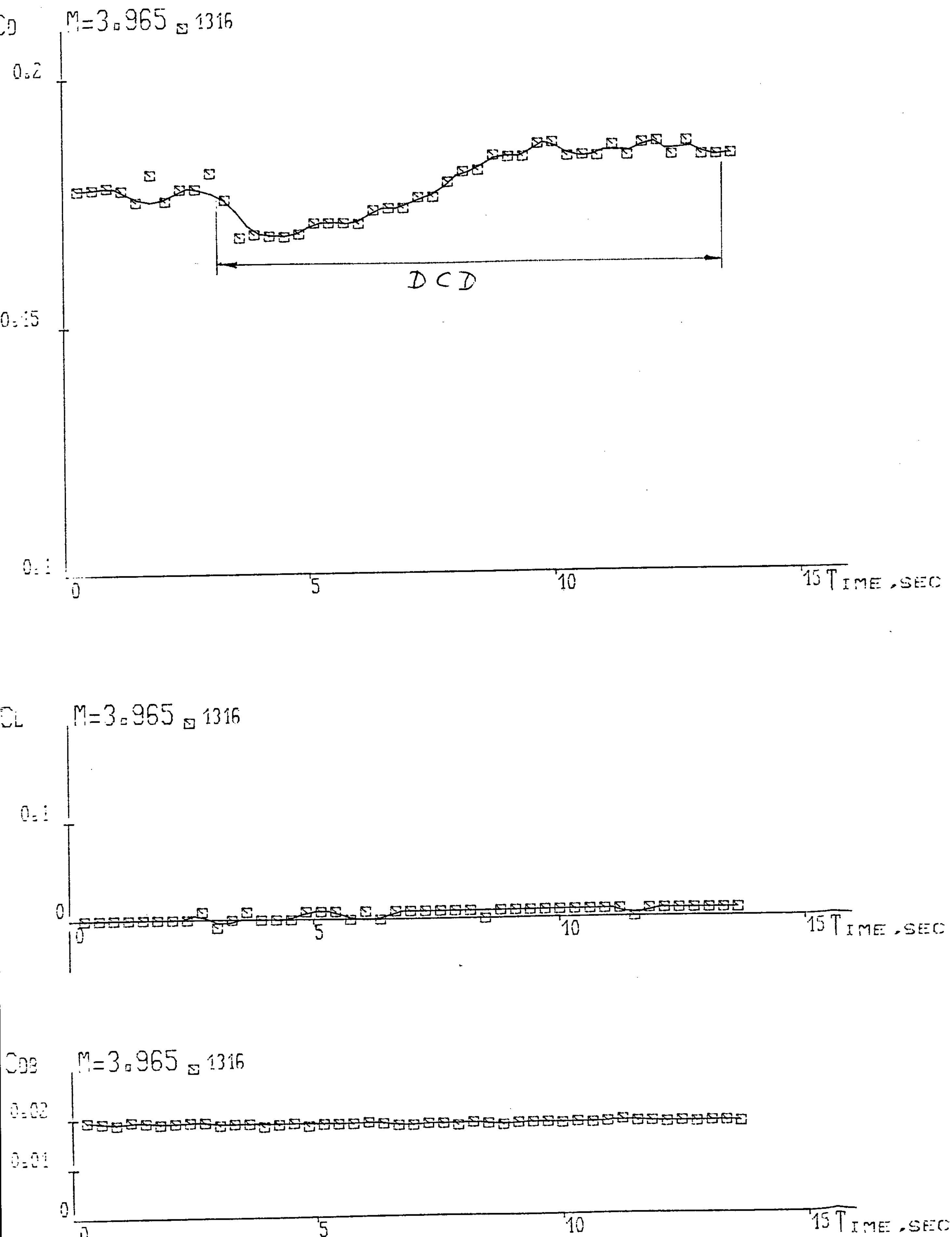


Fig.26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0.1
DCD
0
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10
15 TIME ,SEC
CL
M=3.965 1316
0.1
0
0
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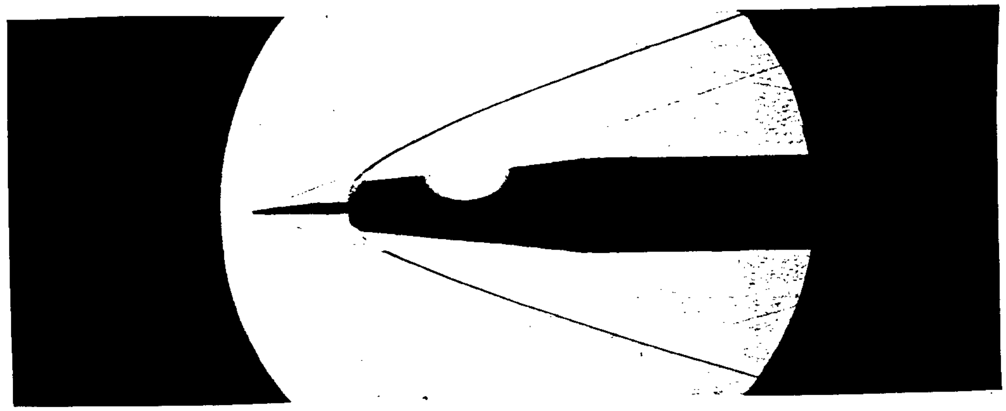
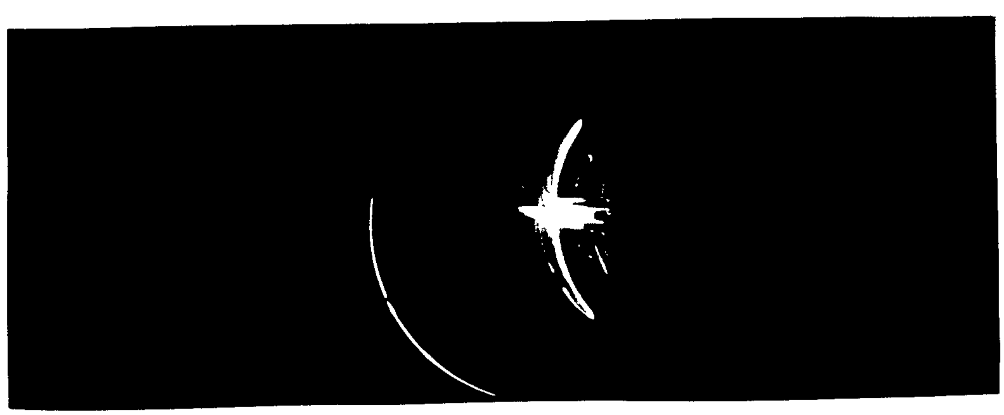
10
15 TIME ,SEC
CDB
M=3.965 1316
0.02
0.01
0
0
5
10
15 TIME ,SEC

Fig.27



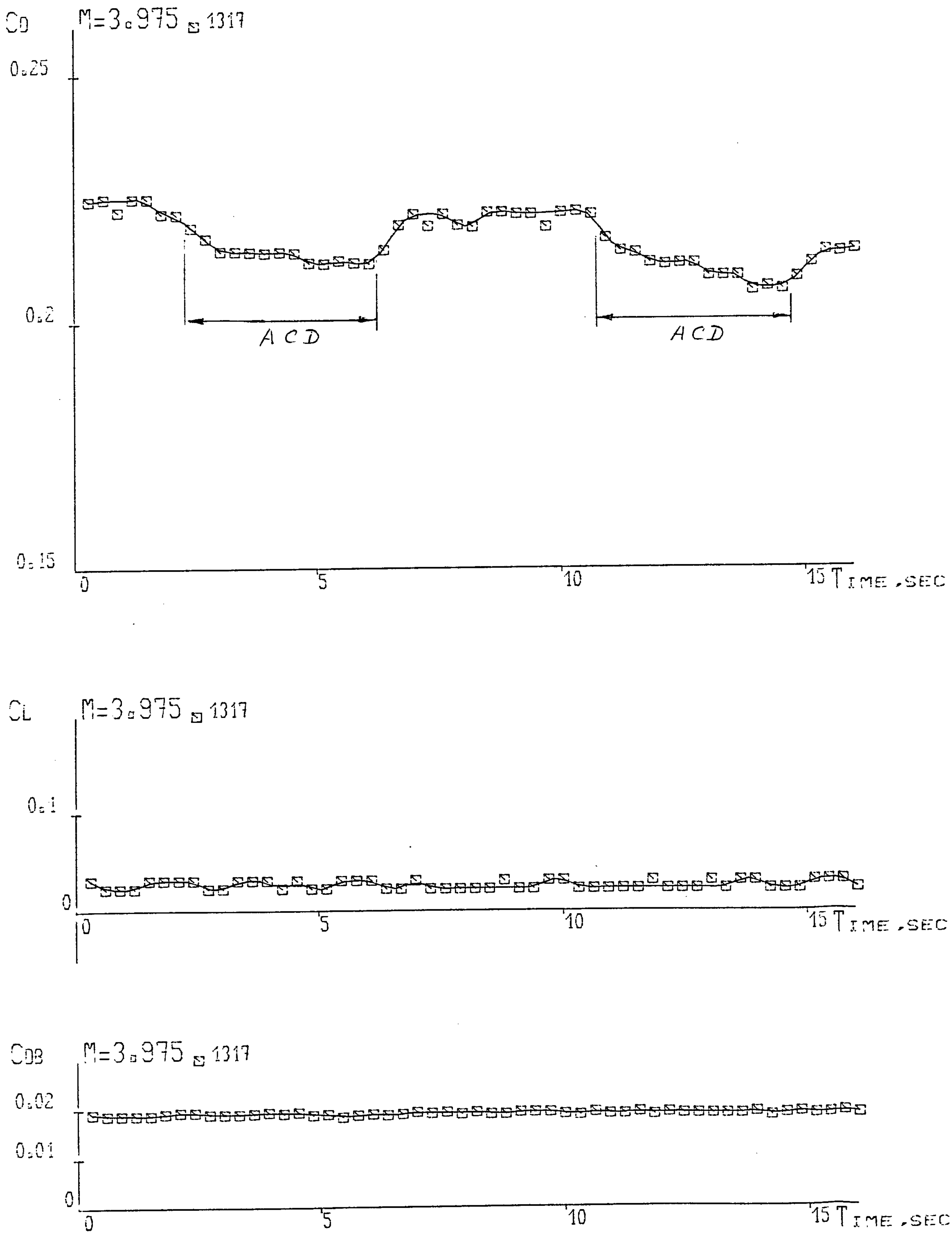
A

B



C

Fig.28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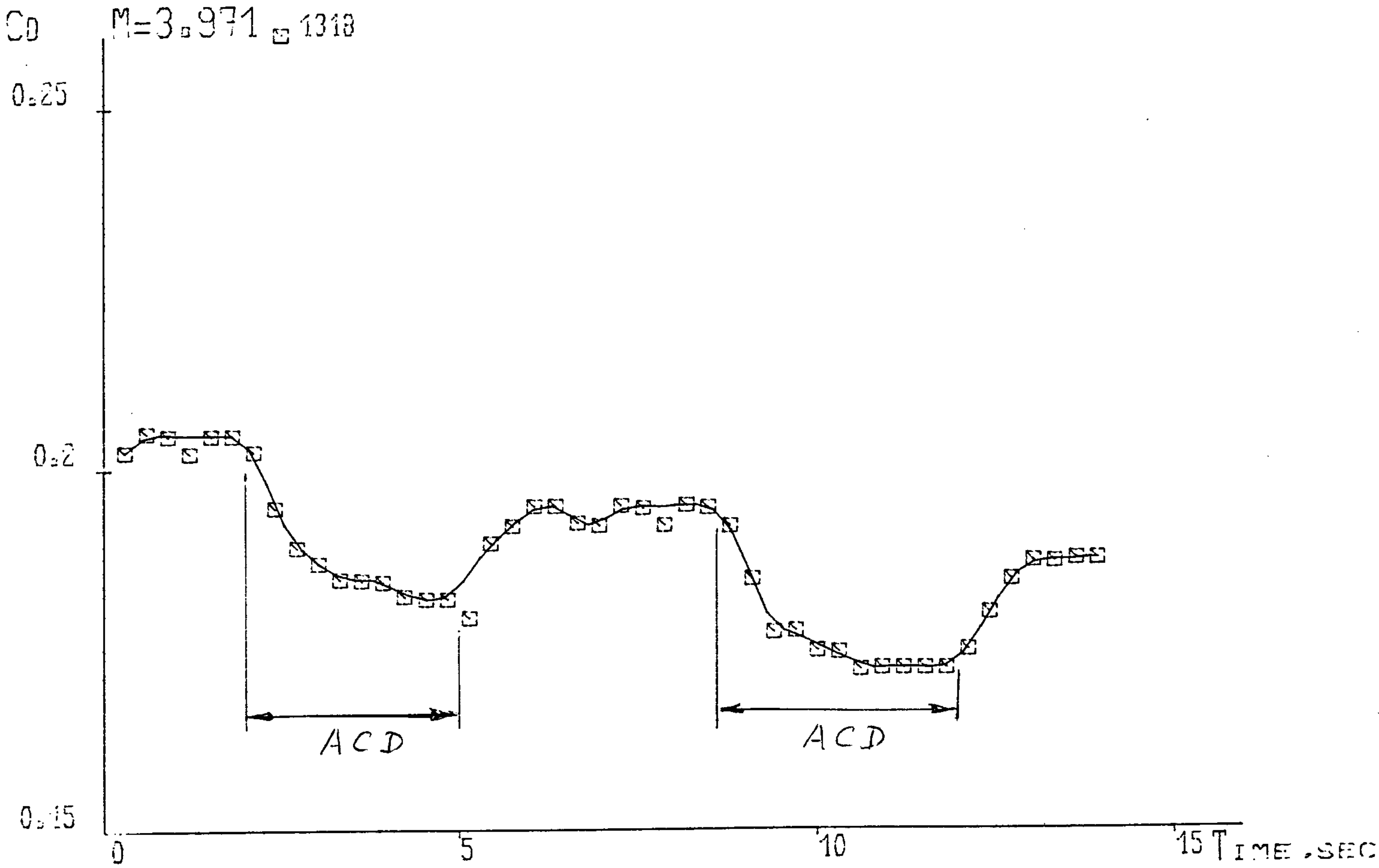
0.15
ACD
ACD
0
5
10
15 TIME, SEC
CL
M=3.975 1317
0.1
0
0
5
10
15 TIME, SEC
CDB
M=3.975 1317
0.02
0.01
0
0
5
10
15 TIME, SEC

Fig.29

A

B

Fig.30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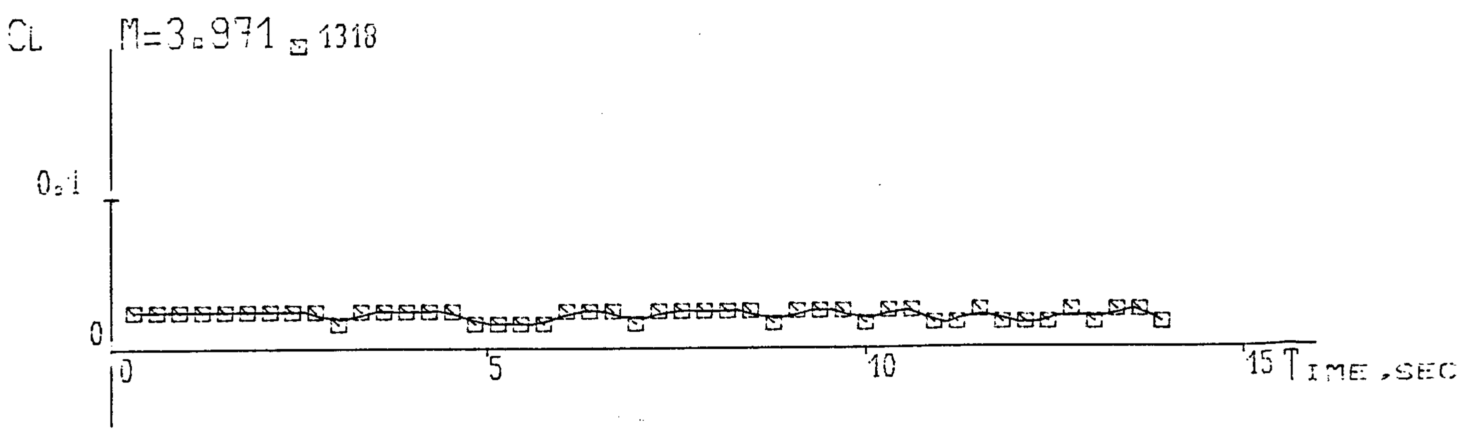
ACD
ACD
0
5
10
15
TIME, SEC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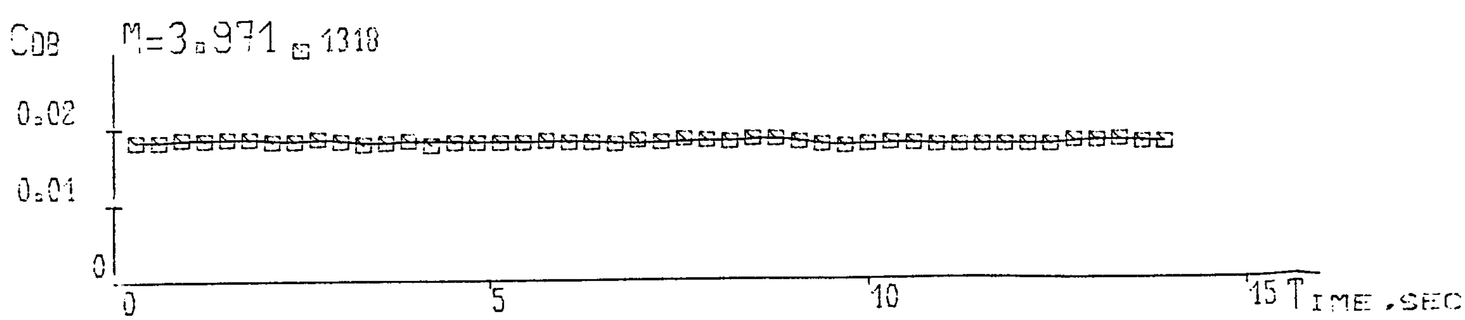
0
0
5
10
15
TIME, SEC


CDB
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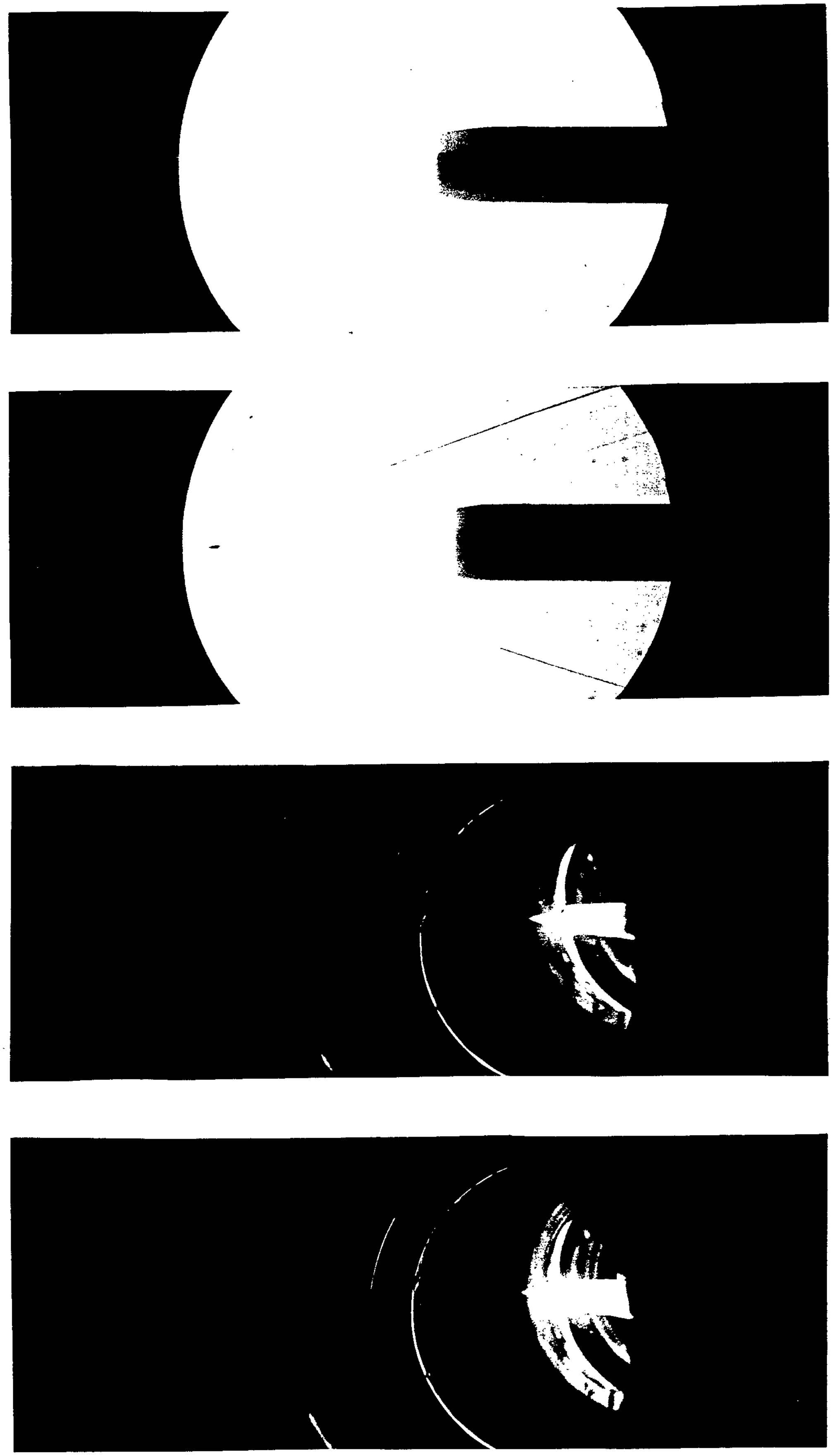
0.01
0
0
5
10
15
TIME, SEC

Fig.31



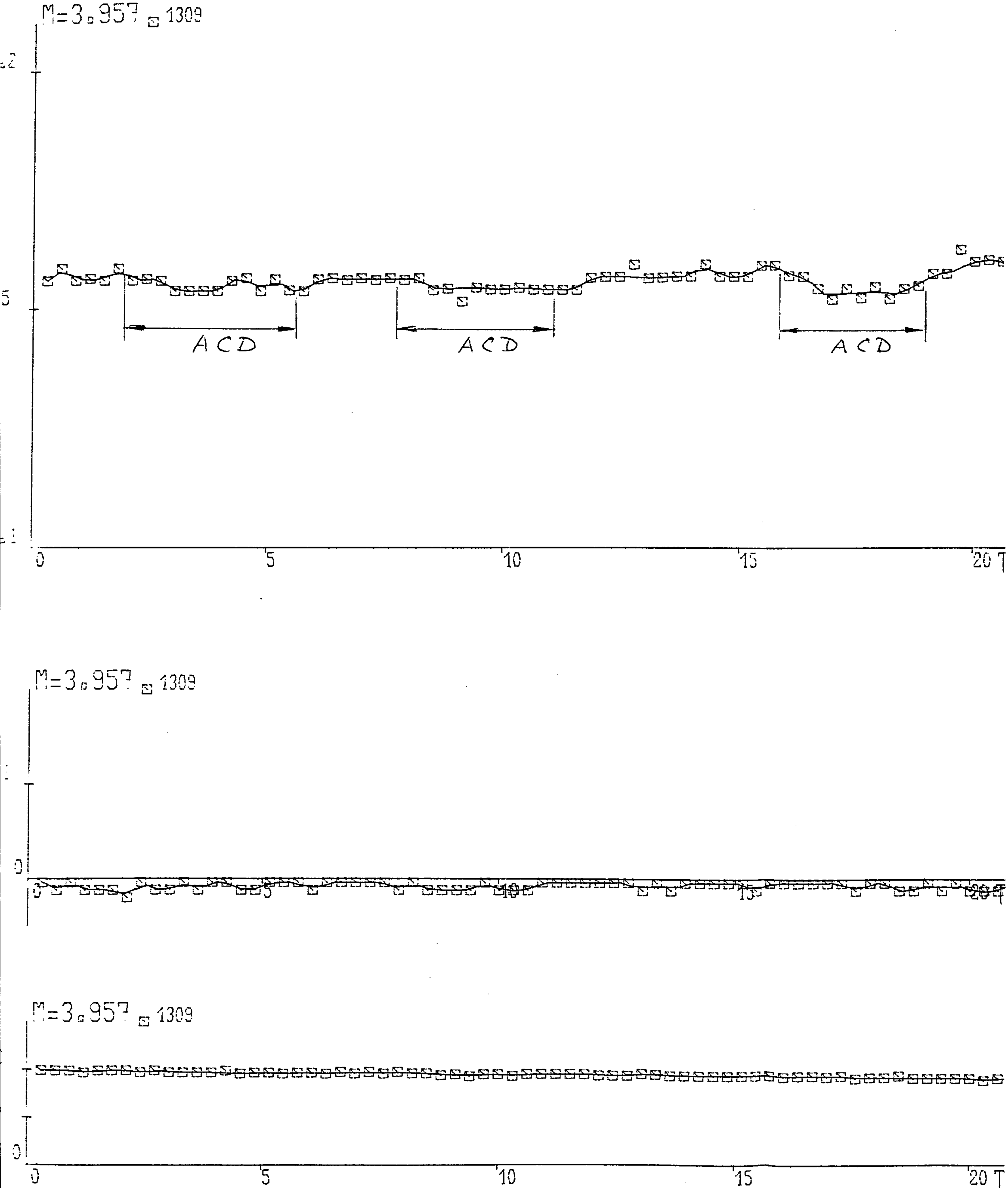
A

B

C

D

Fig.32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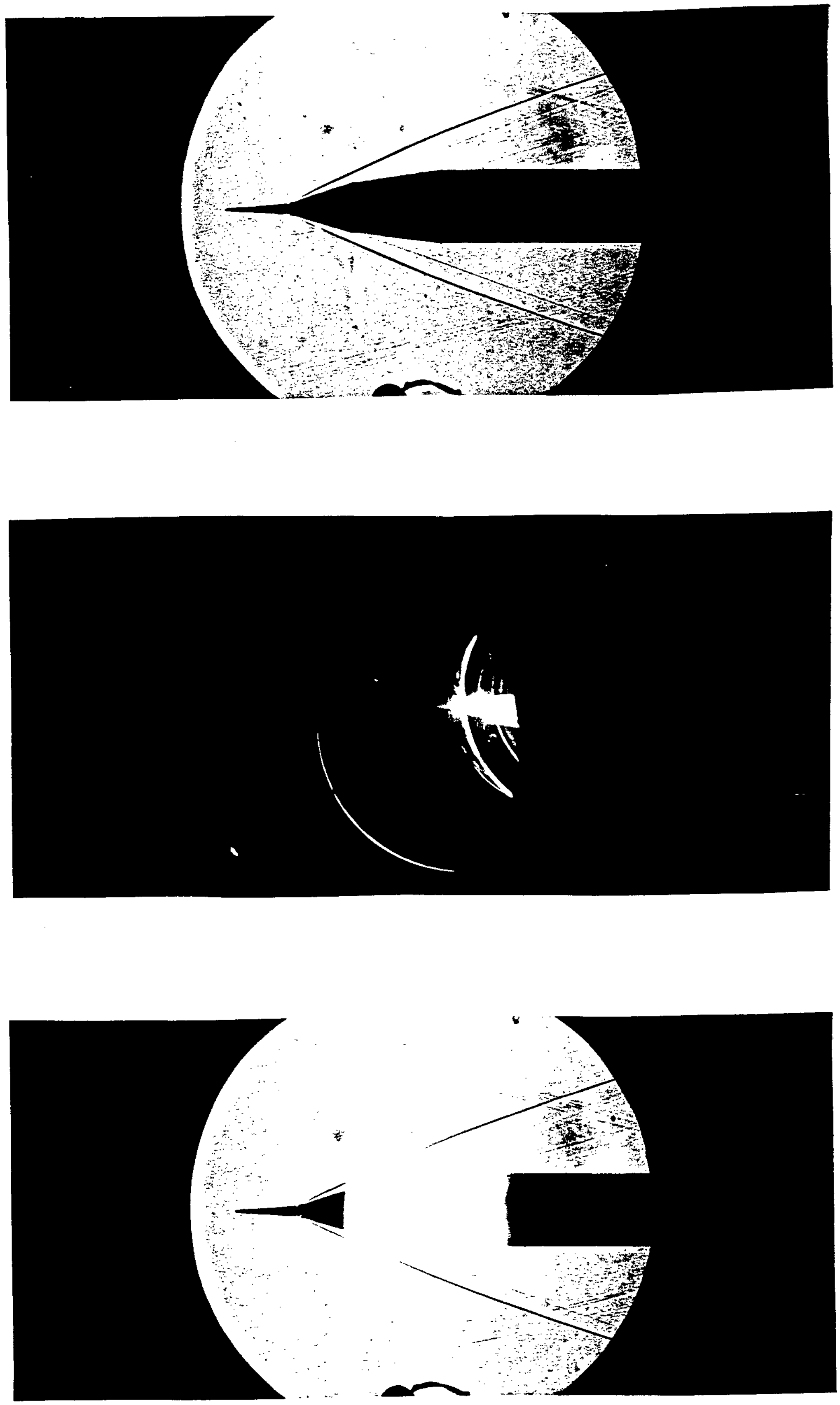
ACD
ACD
ACD
0
5
10
15
20 T
M=3.957 1309
M=3.957 1309
0
5
10
15
20 T

Fig.33

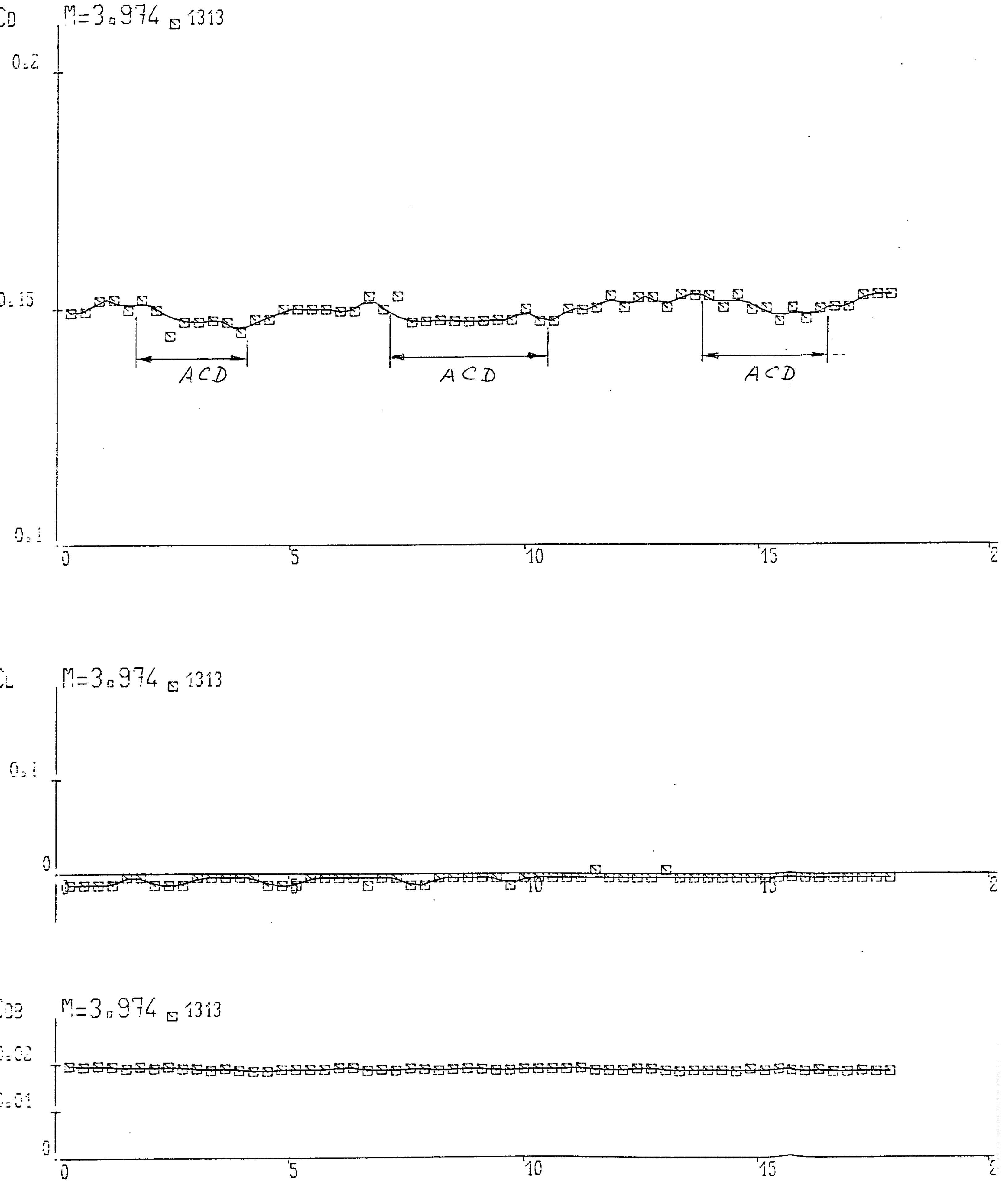


A

B

C

Fig.34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0.1
ACD
ACD
ACD
0
5
10
15
CL
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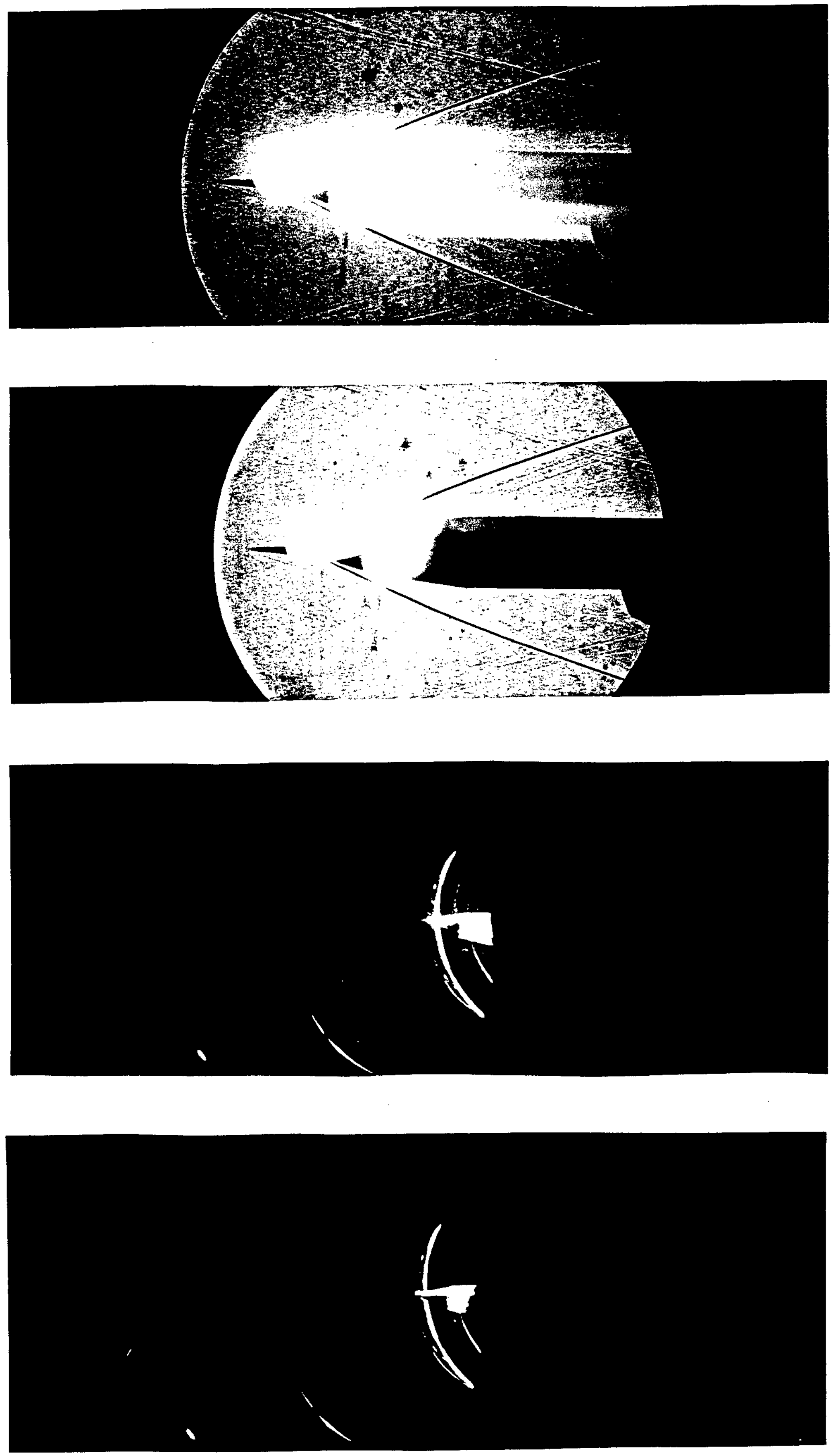
0
CDB
M=3.974 1313
0.02
0.01
0
0
5
10
15

Fig.35



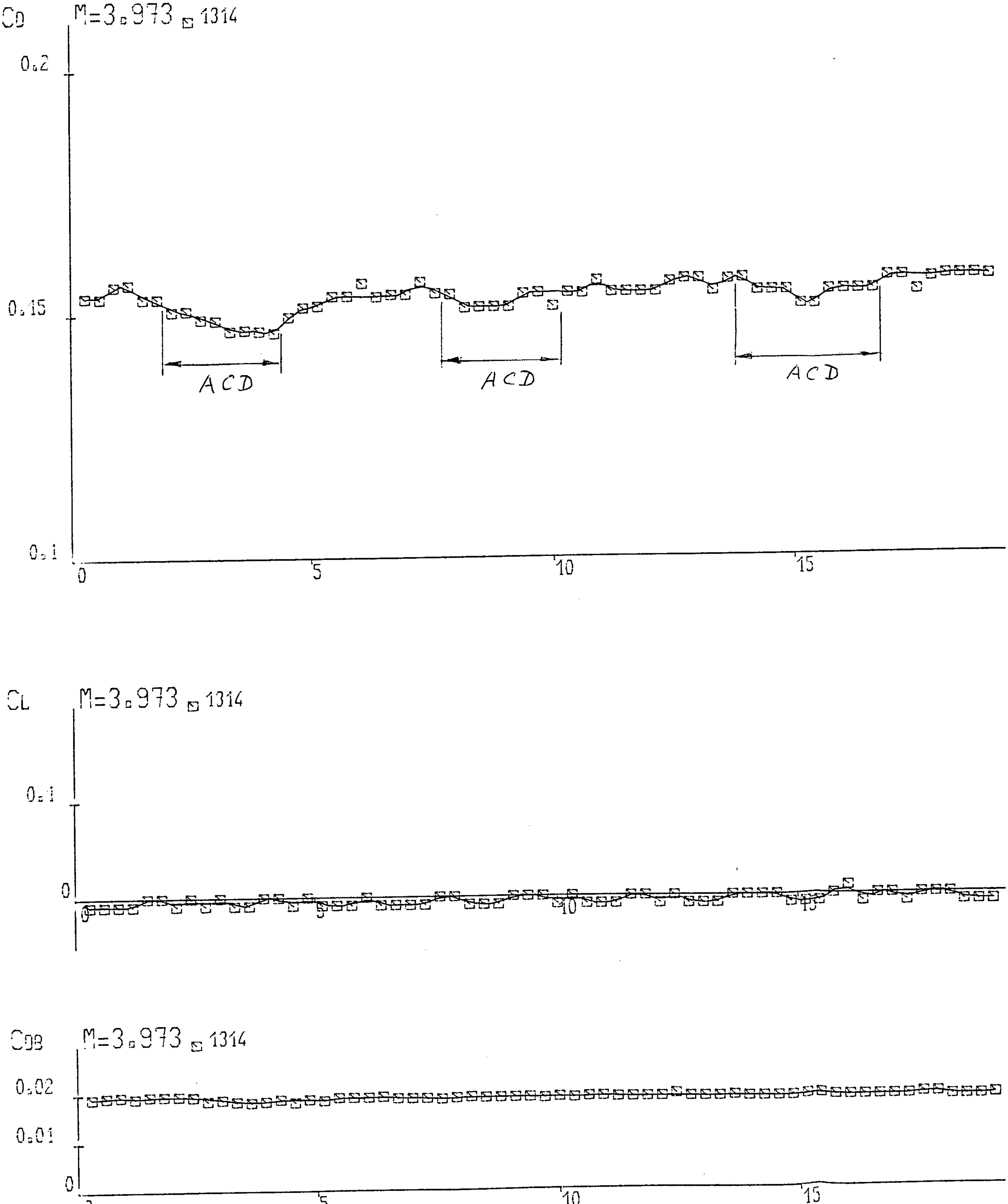
A

B

C

D

Fig.36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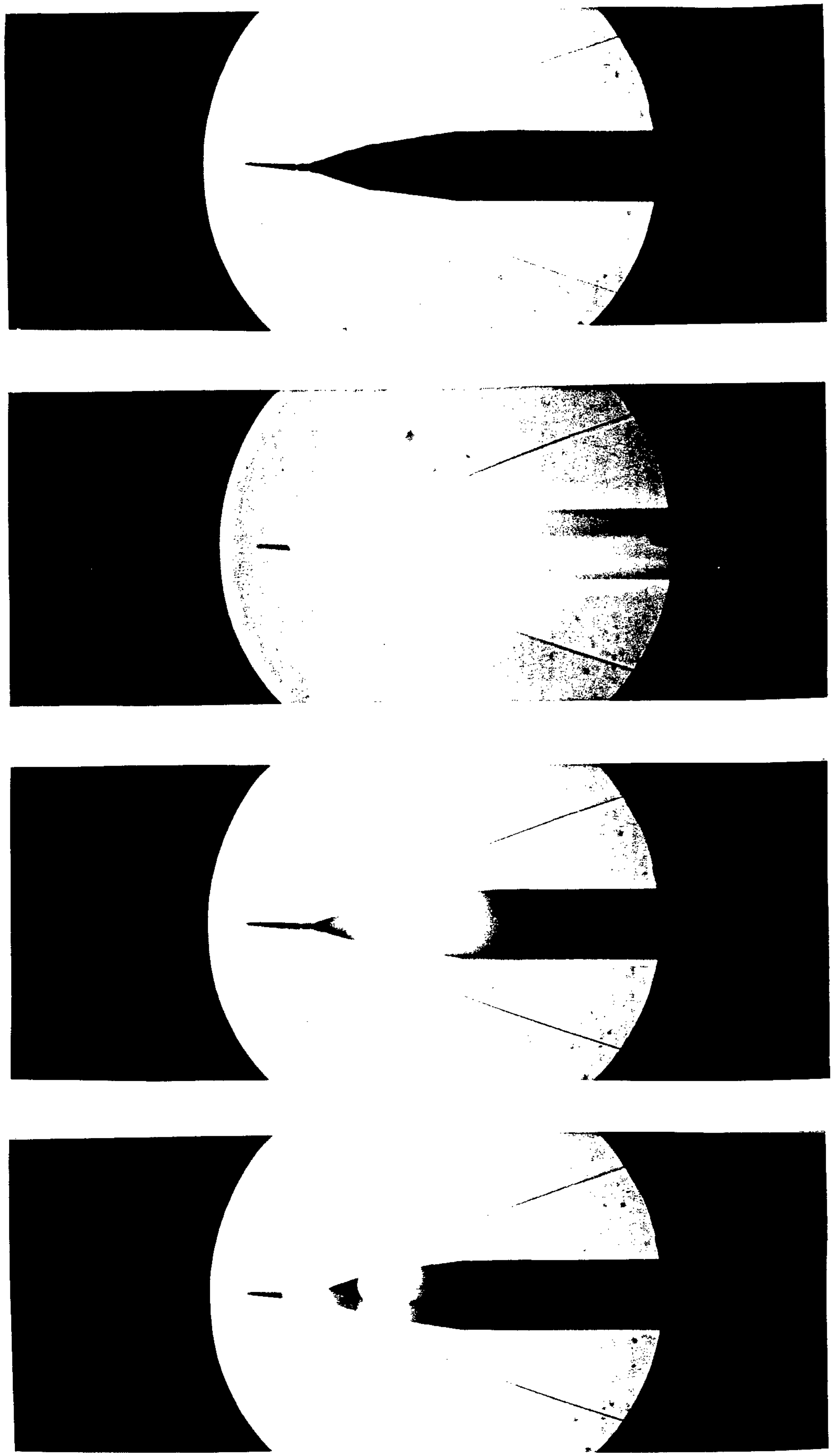
0.1
ACD
ACD
ACD
0
5
10
15
CL
M=3.973 1314
0.1
0
0
5
10
15
CDB
M=3.973 1314
0.02
0.01
0
0
5
10
15

Fig.37



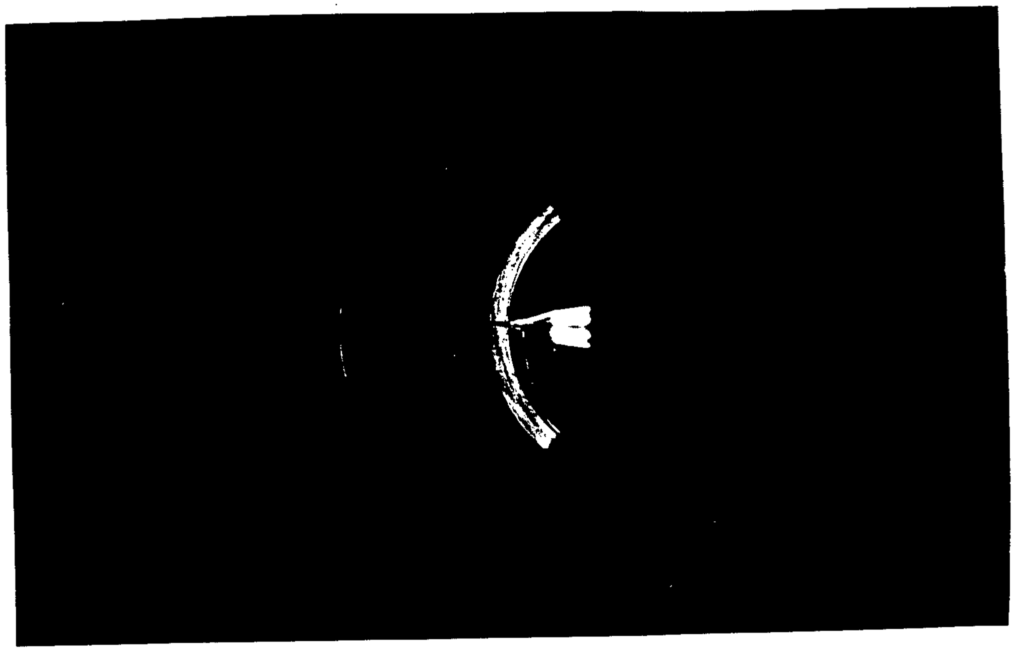
A

B

C

D

Fig.38



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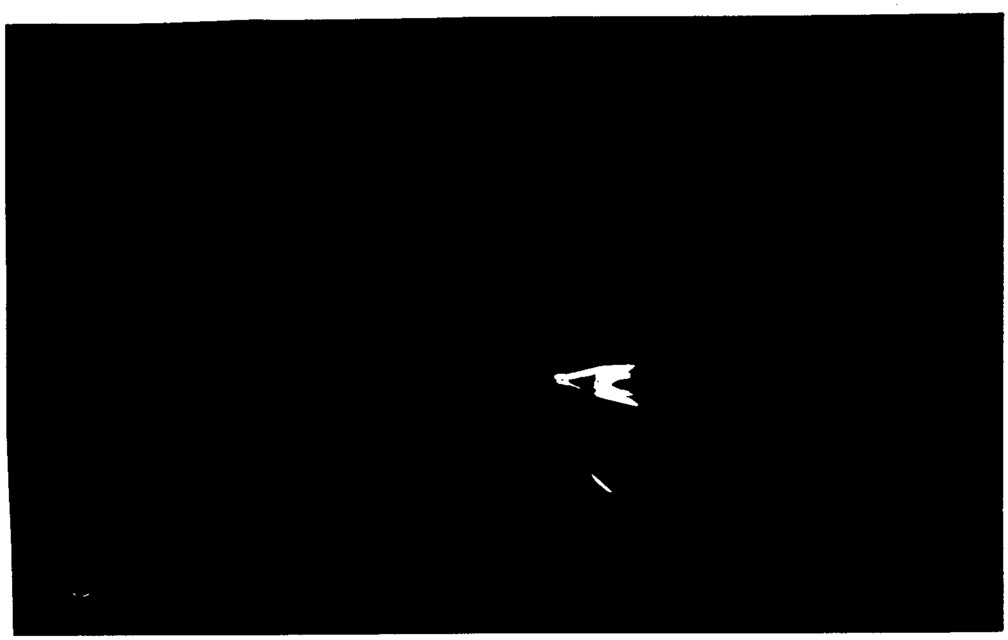
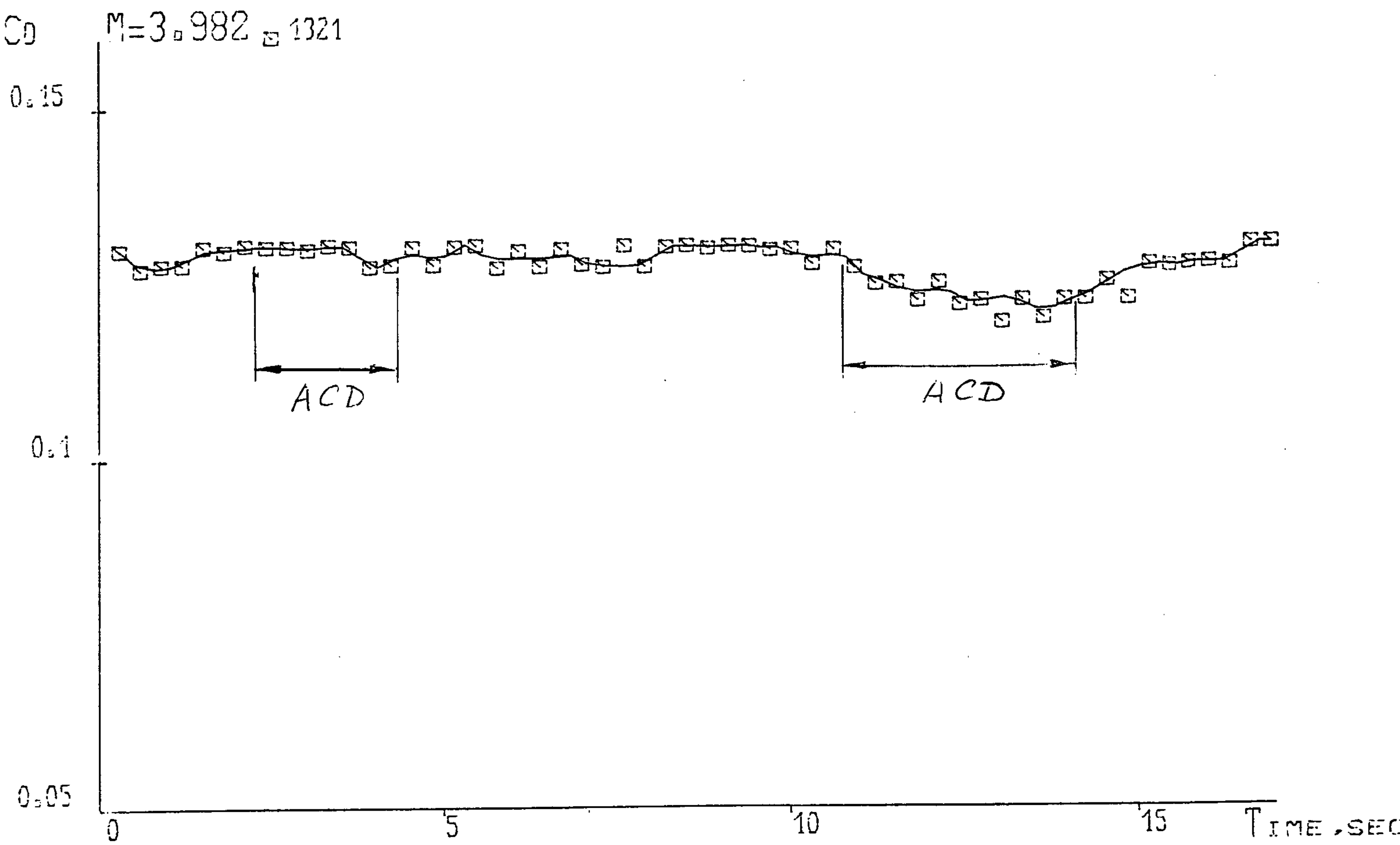


B

Fig.39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ACD
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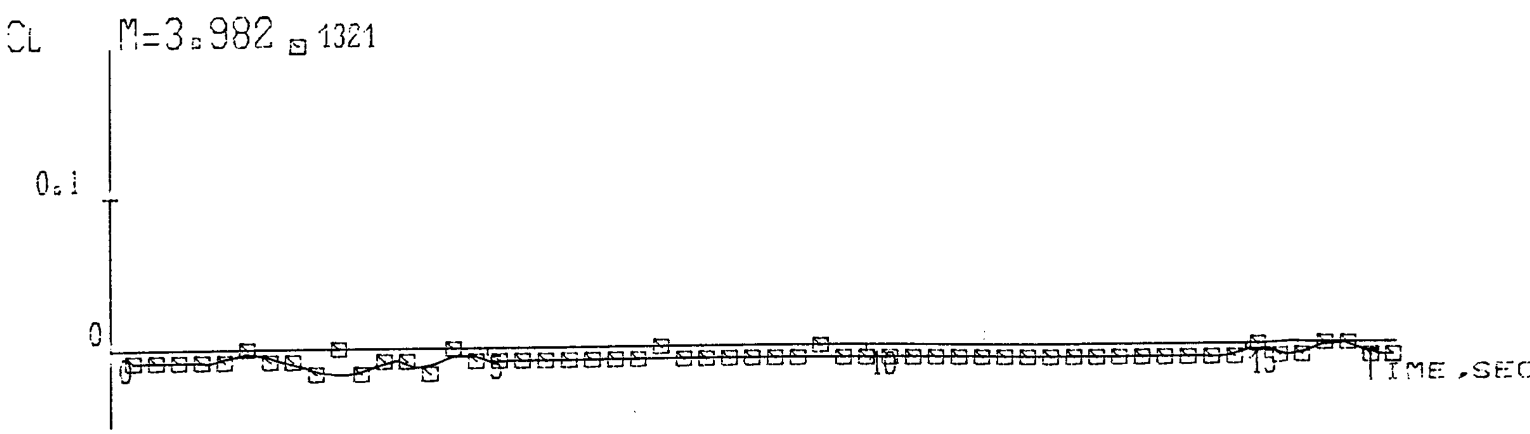
5
10
15
TIME, SEC


CL
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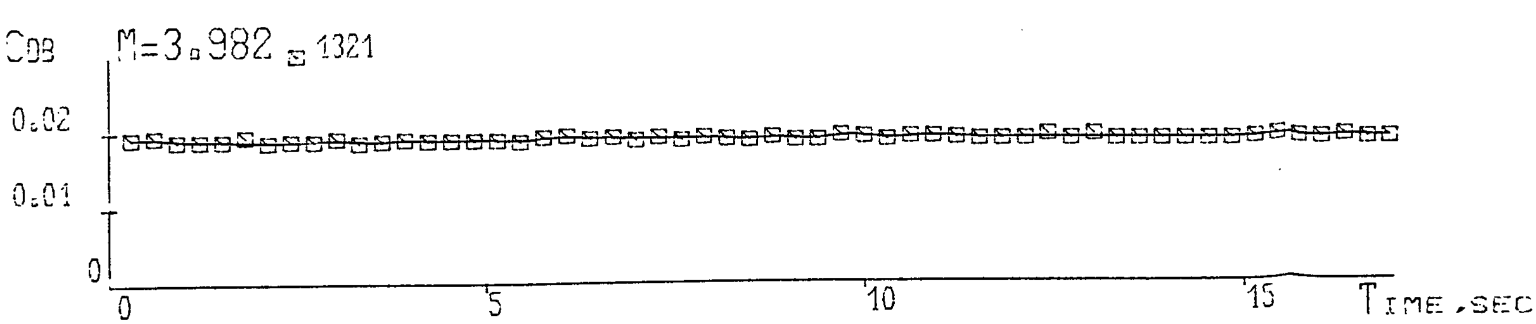
0.1
0
TIME, SEC


CDB
M=3.982 ☒ 1321
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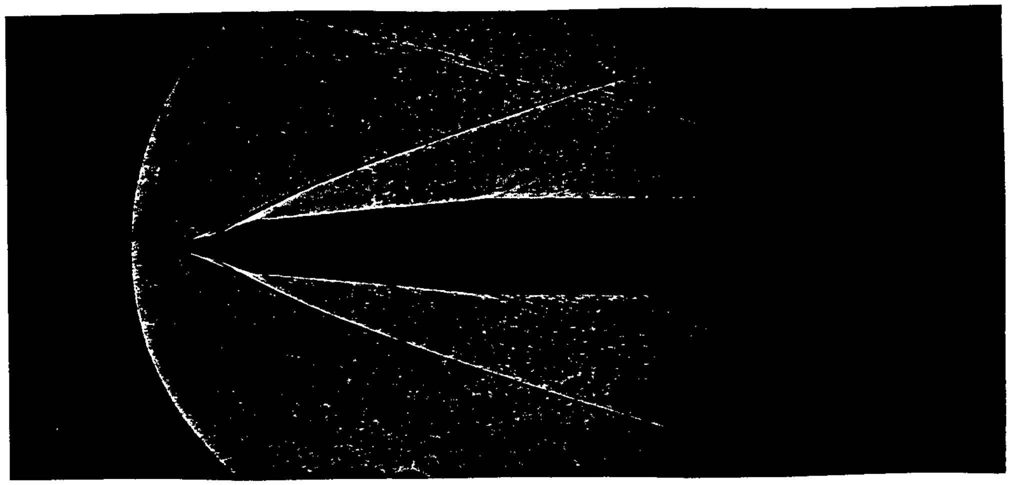
0.01
0
0
5
10
15
TIME, SEC

Fig.40



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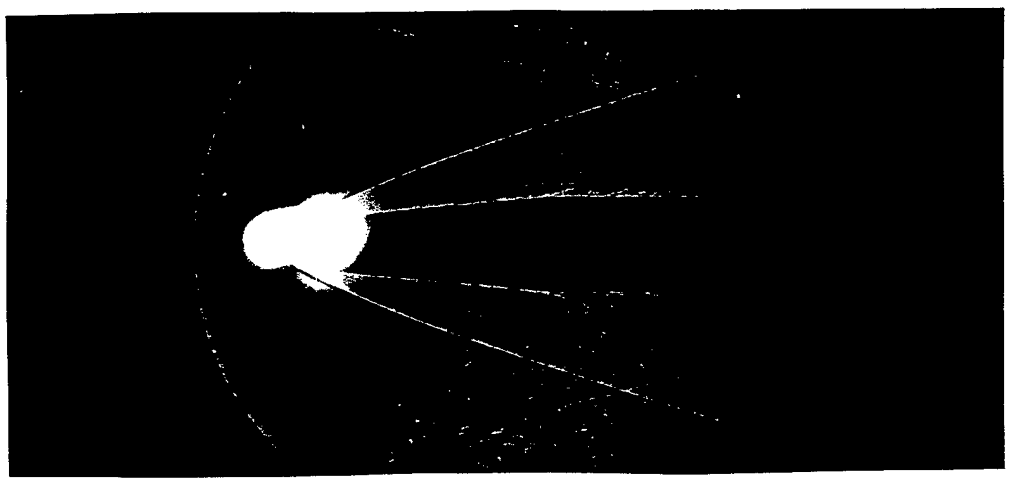
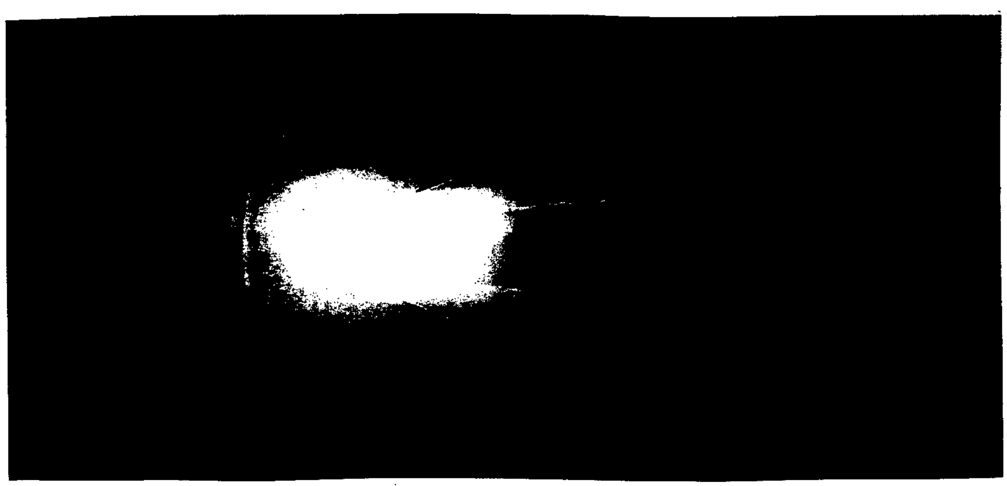
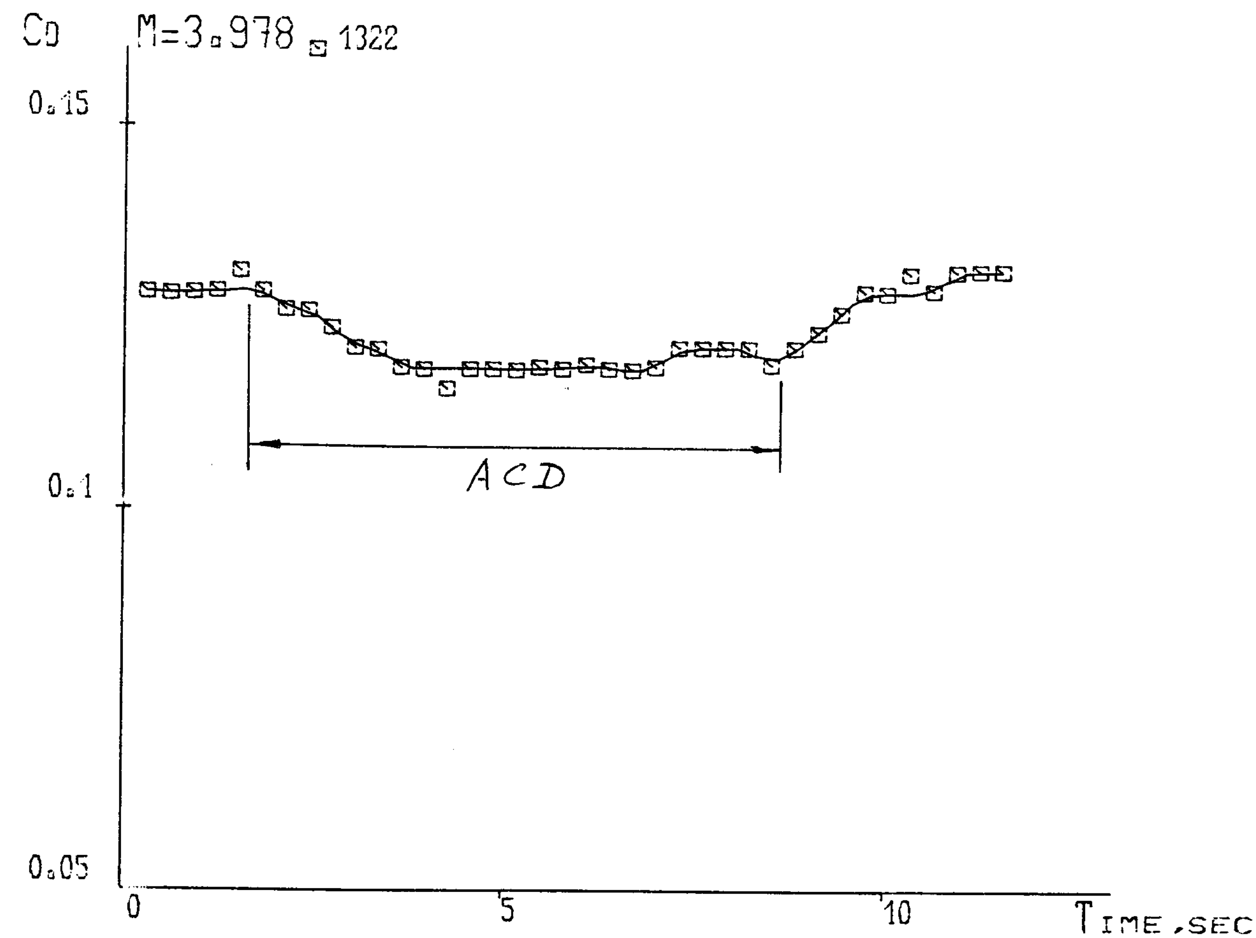


B



C

Fig.41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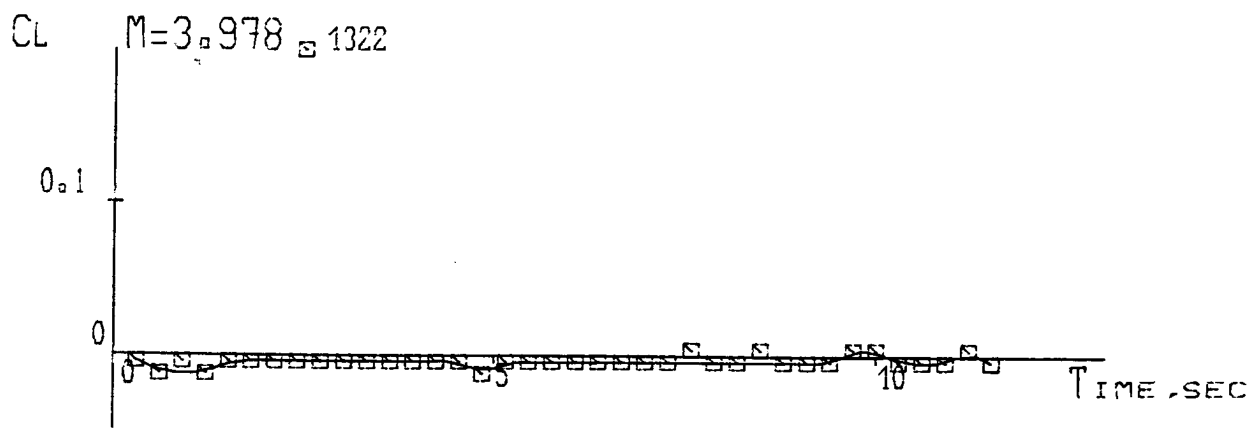
TIME, SEC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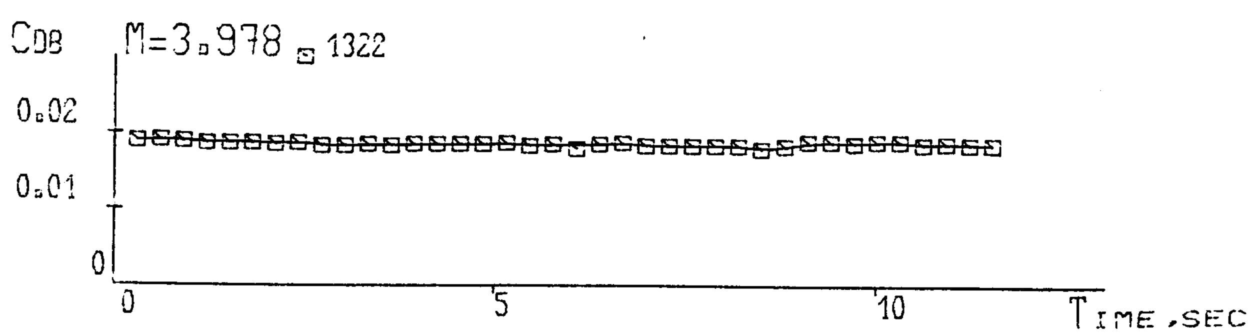
TIME, SEC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10
TIME, SEC

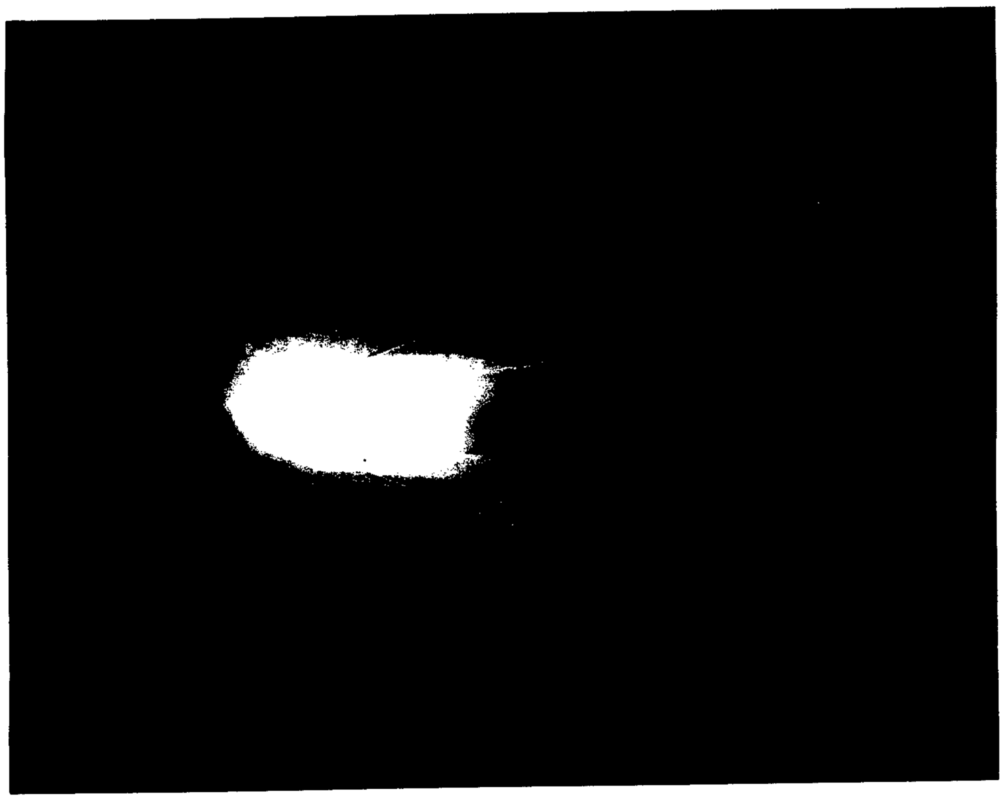


Fig.43

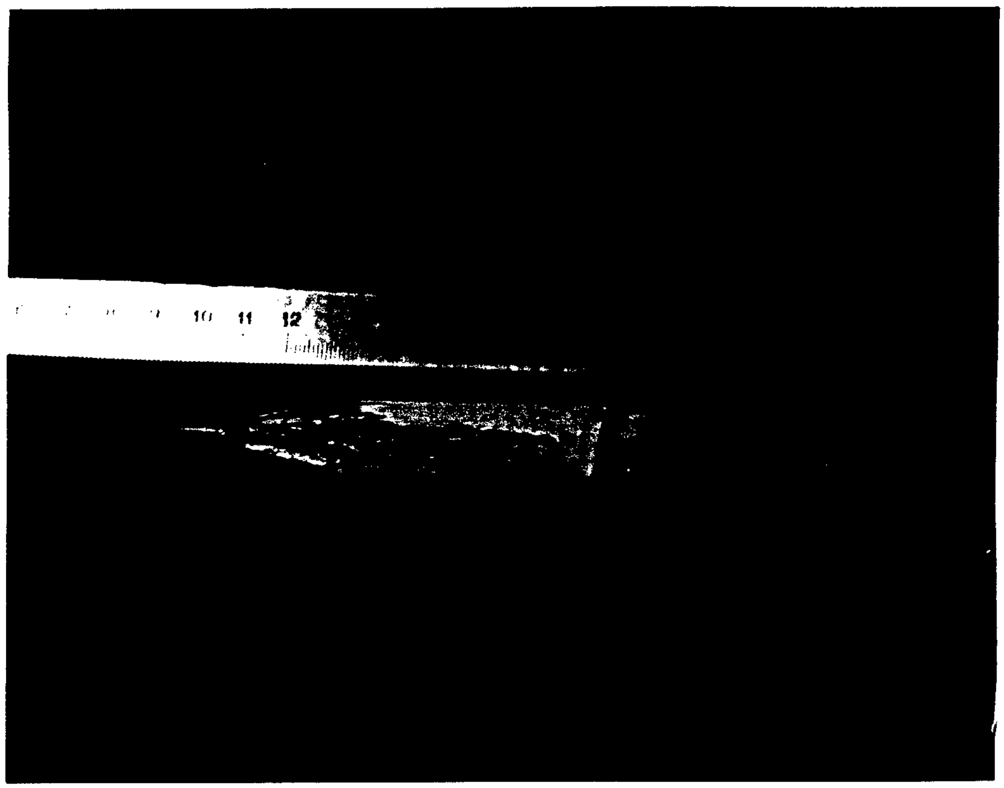
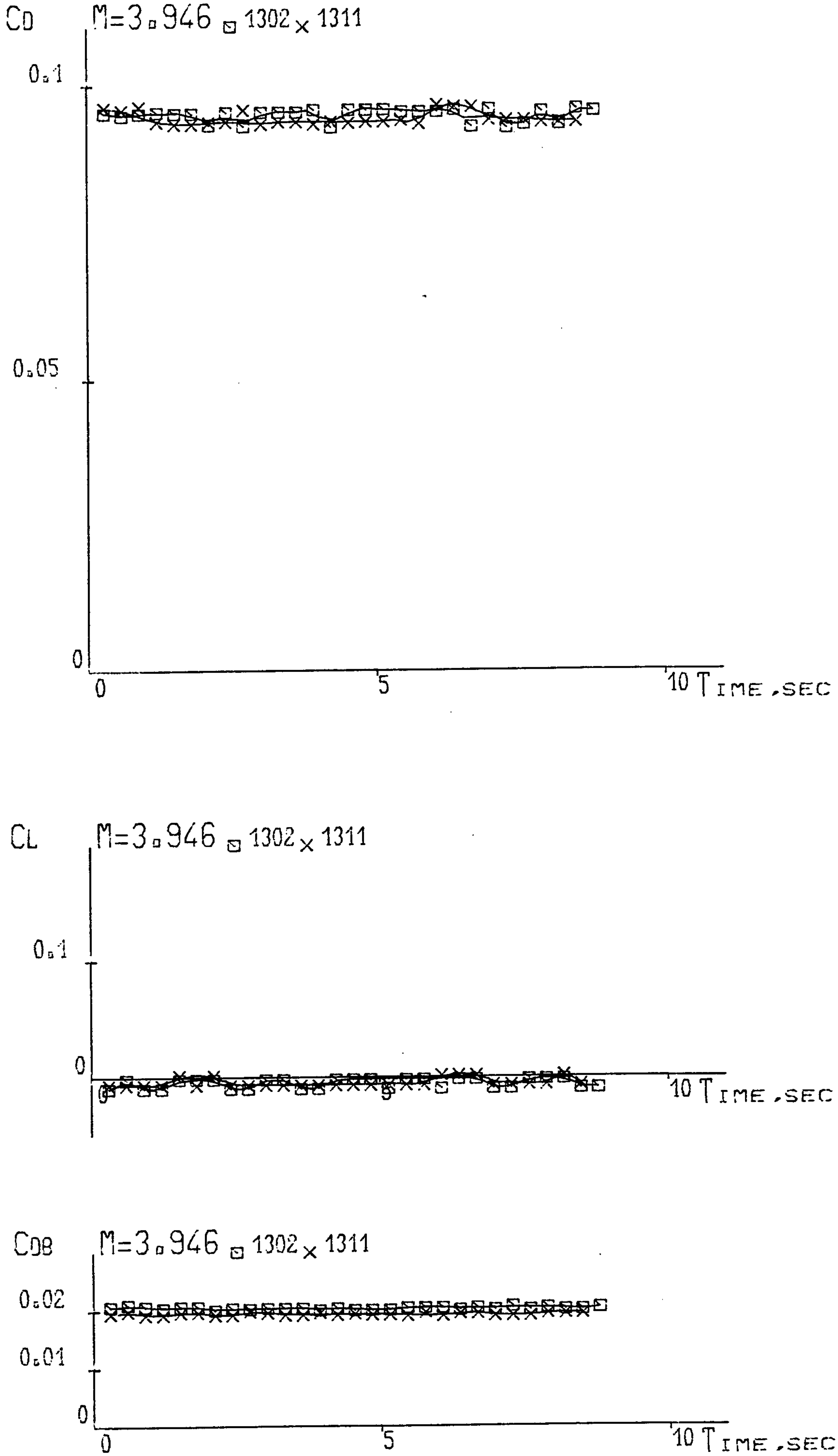


Fig.44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0.05
0
0
5
10 TIME, SEC
CL
M=3.946 1302 × 1311
0.1
0
10 TIME, SEC
CDB
M=3.946 1302 × 1311
0.02
0.01
0
0
5
10 TIME, SEC

Fig.45

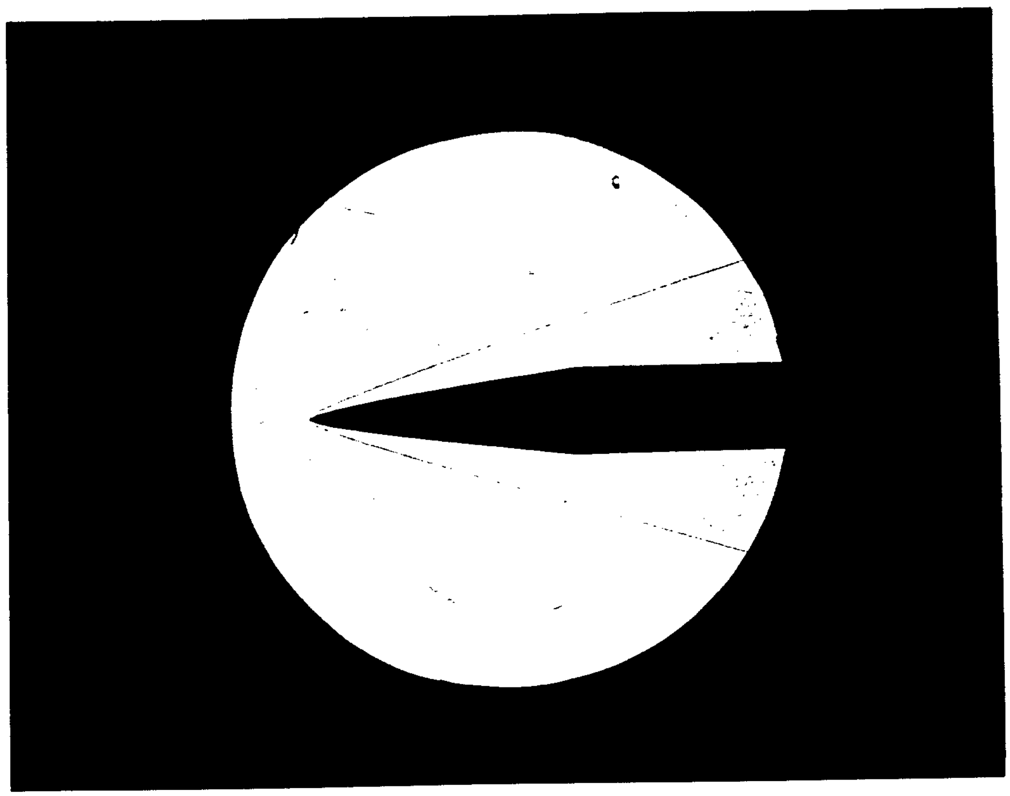
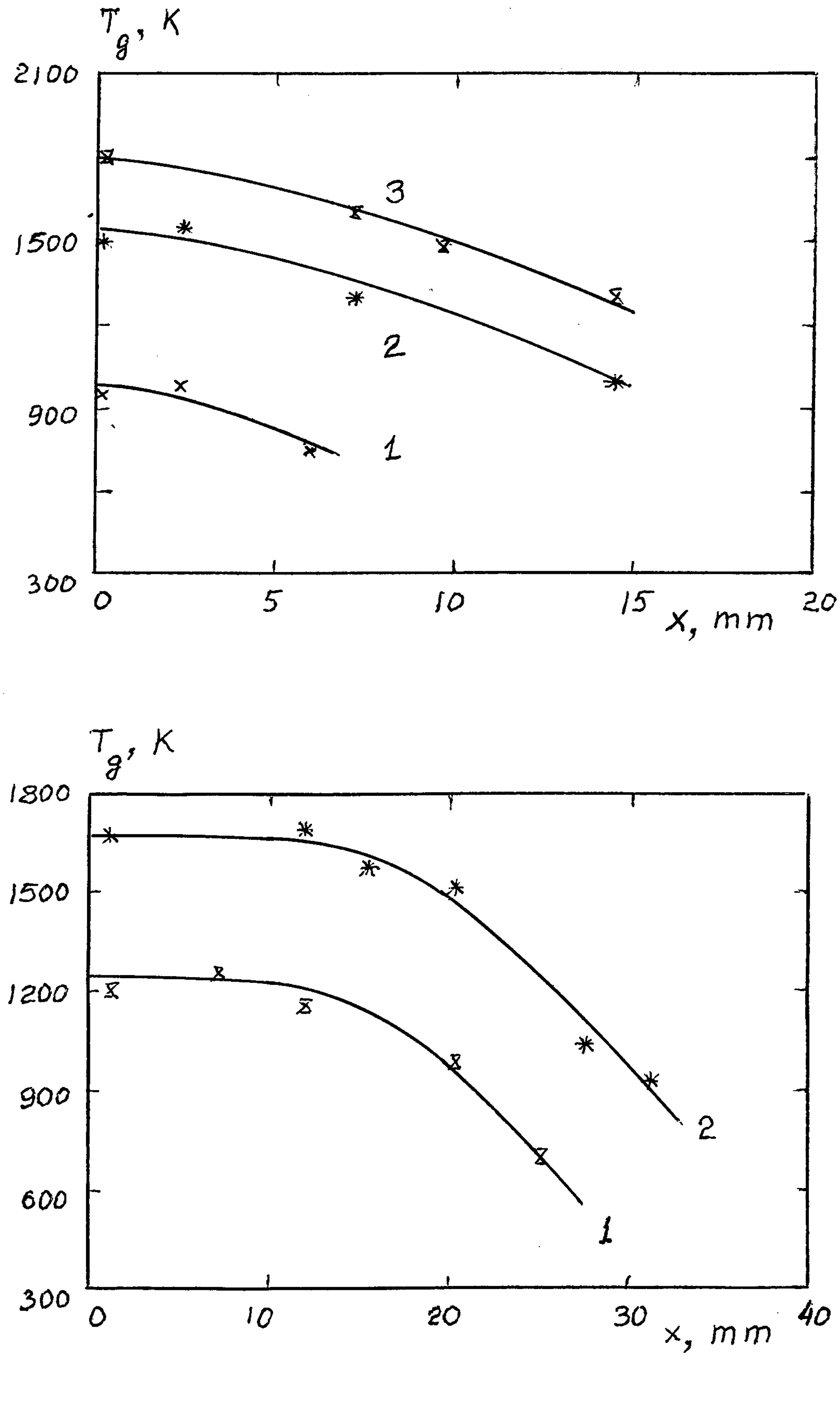


Fig.46



T_g, K
2100
1500
900
300
0
5
10
15
20
x, mm
1
2
3
T_g, K
1800
1500
1200
900
600
300
0
10
20
30
40
x, mm
1
2

Fig.47

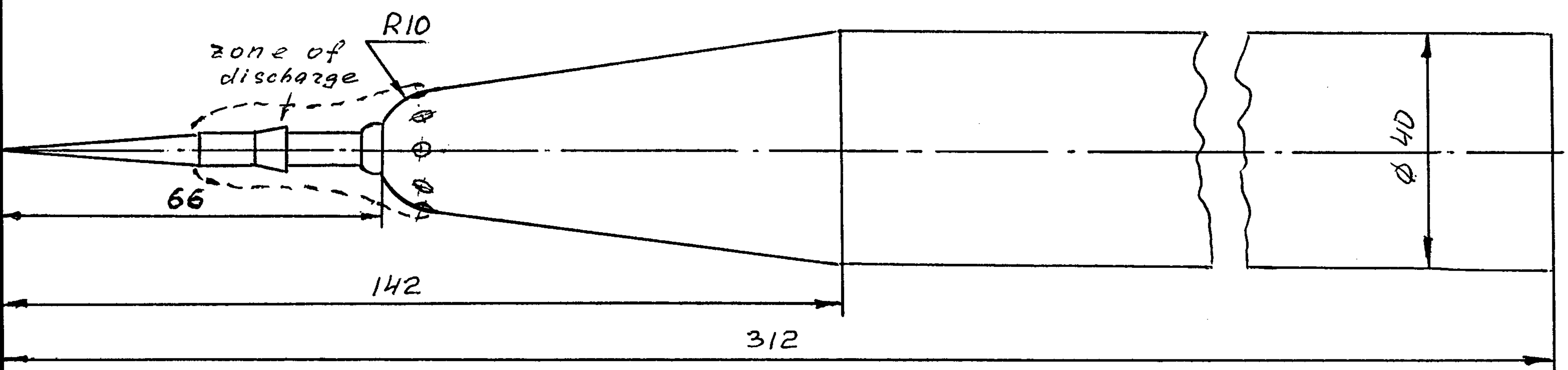
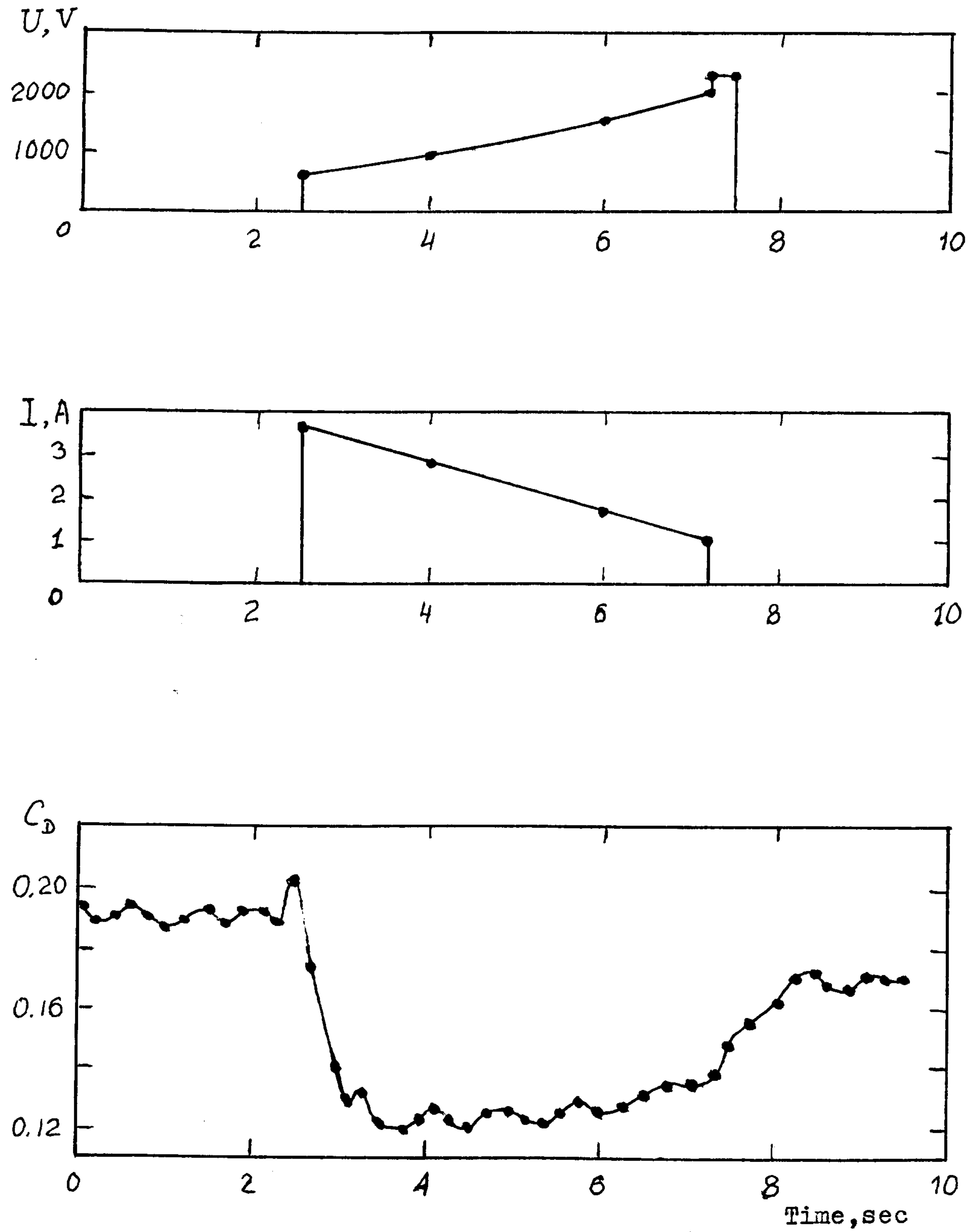


Fig.48



U,V
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1000
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2
4
6
8
10
I,A
3
2
1
0
2
4
6
8
10
C_D
0.20
0.16
0.12
0
2
4
6
8
10
Time,sec

Fig.49